EASY LESSONS IN LIGHT

MRS. W. AWDRY

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EASY LESSONS IN SCIENCE.

EDITED BY PROFESSOR W. F. BARRETT.

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MRS. W. AWDRY.

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PREFACE.

This little book was begun many years ago, simply from love of the study of Light, and has grown slowly to its present shape, every source of information on the subject within reach having been freely laid under contribution.

During the course of learning and teaching on this subject I have been strongly impressed by one point, viz., the wonderful difference in power of sight between trained and untrained eyes, and at the same time the small amount of training necessary to set the eye almost unconsciously educating itself in delicate and accurate vision.

I once asked a lady to look through her fingers at a distant candle, and tell me what she saw. She answered, in perplexity, that she saw the candle, and was eager to know what she was expected to see. This I declined to tell her, but invited her to go on looking, and say from time to time if anything fresh came in sight. Before ten minutes had elapsed she

described delicate phenomena of diffraction, asserting at the same time that she had just become able to see them.

I may venture to hope that some others also may become better able to see by the help of the simple experiments here described, the whole necessary apparatus for which is contained in the following list :—

Pasteboard.	Piece of smooth flat glass.
Tin biscuit-box.	Piece of silvered looking-glass.
Tumbler of water.	Glass prism.
Mounted globe.	Large and small lens.
Three screws.	Two spectacle lenses of long focus.
Walking stick.	Sheet of glazed writing paper.

Small pair of wheels, loosely mounted and running easily.

If possible, a small direct vision spectroscope.

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CHAPTER I.

LIGHT.

1. When a candle is lighted in a dark room, that which we call Light begins to pour out from the candle all round. Some of it comes straight to our eyes, and then we see the candle: some of it knocks against the things in the room—tables and chairs, floor and ceiling, and these things as soon as it touches them change its direction and begin to scatter or send it out round themselves in turn. Some of this again reaches our eyes, and then we see the last thing against which it struck.

2. We may easily convince ourselves that light does pour off from the candle flame equally in all directions by observing that it makes no difference to its brightness whether we see it from above or below or either side, provided the distance is the same and nothing else gets in the way. This would not be the case if more of the light went in one direction than in another.

On looking at a gas lamp through a fog we can see (by the help of the fog) the outpouring light, and may

observe that it is in the form of a sphere with its outer edge passing gradually into dimness and darkness. And, indeed, the least consideration will show that anything which moves out from a centre with equal rapidity, in all directions, must be spherical in form.

In the same manner, not only things which shine by their own light, but everything we see and every part of everything we see, is pouring out light, which starts away from it as the threads of a mop fly out from the centre when it is twirled, and travels on constantly straight forward until it hits against something which either stops it or changes its direction.

But there is one important particular in which the outflowing light is not like a twirled mop. Each thread of the mop stands out straight by itself with a blank space all round between it and the next. But with the light there are no blank spaces; the outward movement is in this respect more like that of the film of a soapbubble which moves out gradually in all directions as it is blown out larger and larger.

3. And just as the soapbubble gets thinner and thinner the larger it is blown, so the light is strongest and brightest close round the point which sends it out, becoming more diffused and less intense as it spreads further from this centre. Or, still more accurately, the gradual diminution of the light may be compared to the ring of ripples made by dropping a stone into a pond—the wave ring becomes larger and at the same time lower and less conspicuous as it spreads out round the spot where the stone fell, just as the spheres of light become larger and fainter as they spread further from their starting point.

Fig. 1 is intended to represent a section through the centre of a sphere of light; the brighter centre stands for the intenser light, which gradually becomes diffused until beyond a certain distance it ceases to strike the eye as light at all. If your eye comes within the range of the light where it is not too much diffused, the central object is in sight. For instance, let us suppose a candle to stand at the central point marked A in Fig. 1; then on placing your eye at B you will see the candle by means of its own diffused light. If we draw a straight line joining A and B, this will represent what is called a *ray of light*, that is to say, the line of direction in which the light reaches the eye.

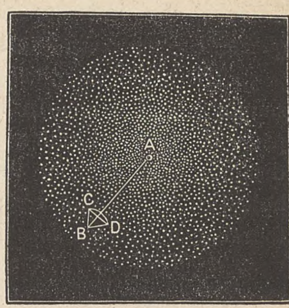


Fig. 1.

4. The intensity of the light diminishes at a regular rate as it extends farther from the centre.

Suppose we were to enclose a lamp in two clear glass globes, the second of which is twice as far from the lamp as the first; then the second being twice as wide and twice as high will have a surface four times as large as the first. We will suppose both to receive the same amount of light from the lamp, but by the time it reaches the second it is spread over four times the space, so that any one part of the second gets only a quarter as much light as an equal part of the first globe.

Again, if we could surround the lamp by a third

globe, at three times the distance of the first, its surface would be nine times as large, and each part would only receive $\frac{1}{9}$th of the light received by an equal part of the first globe. So then at twice or three times the distance, the intensity of the light will be one quarter or one ninth, and so on.

5. The same thing can be shown by the following simple experiment:—In front of a lamp or candle place a card screen with a hole in it. Then if at a fixed distance, as at C, fig. 2, the light coming through the hole just illuminates 1 square inch of card, it will be found that at twice this distance it will illuminate a

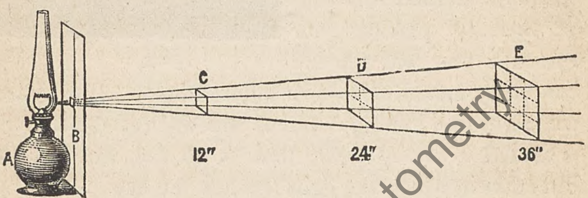


Fig. 2.

card 4 inches square; at three times the distance, a card 9 inches square, and so on; and, of course, the same amount of light spread over nine times the space is dimmer everywhere.

The usual way of expressing this rule is—The intensity varies inversely as the square of the distance, and it is briefly called *The Law of Inverse Squares.*

6. The distance within which objects are visible varies enormously according to the first intensity of the light, and the consequent distance which it reaches before it is entirely diffused. Consider, for instance, what must be the size of the spheres of light emitted

by the fixed stars, before they become too much diffused to render the stars visible. Spreading, as we must suppose, equally in all directions, they are large enough to include our earth from which our human eyes see them. And supposing a star to be at such a distance from us that its light reaches our eyes in too diffused a condition to render the star visible to the naked eye, then if we can in any manner gather together into the tiny pupil of the eye a sufficient quantity of the diffused light, the star may be rendered visible.

7. This is the principle of the telescope. Suppose that A (Fig. 1) is the star, and B the eye at such a distance that the starlight is not strong enough to render it visible; if a suitable lens CD can be placed between the eye and the star, it will receive all the diffused light that reaches the space C D, and, owing to peculiar properties of which we shall have to speak hereafter, will bend all the rays in such a manner that they meet on the point B, thus bringing to the eye stationed there sufficient light to render A visible along the line A B, which passes through the centre of the lens, and is called its axis.

8. These spheres of light are invisible. When we look at the stars we see the sky dark round them, though they are pouring out light in every direction. We only become conscious of light when it is arrested by some object capable of scattering it in fresh directions, and so sending it to our eyes. When a ray of sunlight falls through a chink into a darkened room, what do you see? A spot of bright light on the carpet, a number of dancing specks in the

sunbeam, which arrest a portion of light and send some of it to us, and probably a little diffused light on some of the objects in the room nearest the beam, caused by the scattering of light from the spot on the carpet, and from the illuminated motes. But suppose the motes in the sunbeam to be removed, as they have been in some recent scientific experiments by burning them, and what will you see then? The path of the sunbeam will have become totally dark, and all that remains is the spot on the carpet rather brighter than before, and such illuminations as there may be from it. We are not conscious of light till it is arrested, and then we see, not the light, but the object which arrested it, more or less brilliantly.

9. Strange to say, these spheres of light, though pouring out in all directions from everything at the same time, do not ordinarily appear to clash and disturb each other. I am looking out of a window in the west wall of a square court surrounded with buildings, and I see the opposite windows and the steady downfall of rain between. But if there is some one else looking out of a window on the north, he will see all that is on the south side of the court without the least interference from the rays that are pouring from the east side into my eyes on the west. The whole court is full of light going in all directions at once, whether there is any one to see it or not, but each ray keeps to its own business without interrupting its neighbours.

10. These journeys are made with enormous speed. The outward movement of the film of a soap bubble is gentle enough for us to watch its progress, and the

progress of a water wave may be easily traced, but the outrush of a sphere of light is made at the rate of no less than 186,000 miles in a second.

As, according to this, light comes to the earth from the moon in rather less than a second and a quarter, it appeared at first to be impossible to find out the velocity of light by measuring its rate on the surface of the earth, and it was first discovered by means of the movements of the planets and their satellites.

We are able to judge of the distance of a thunderstorm by counting the time between the flash and the report, because we know the different velocities of light and sound. The flash and the report really take place at the same time, and the light of the flash reaches us instantly, but the sound travels only at the rate of about 1,125 feet per second, and consequently by counting the seconds which elapse before it arrives, we shall know what distance it has come. When the flash and the report occur within a second of each other we know that the storm is within about 1,125 feet, or less than a quarter of a mile.

But the distance of the heavenly bodies from us is so great that though light travels with this enormous speed, it "must take 8¼ minutes in reaching us from the sun; about 5 hours in coming from the planet Neptune; not less than years from the nearest fixed star; and probably centuries in coming from the nearest nebulæ; so that we see the nebulæ not as they are now, but as they were some centuries ago" when the light which has just reached us left them.

CHAPTER II.

REFRACTION.

11. When a ray of light falls upon any transparent substance, such as air, water, glass,—part of it is reflected[1] back from the surface, and part passes on through the transparent medium.

This we will immediately prove by experiment before going further, since it is the rule in all scientific work to take nothing on trust from others which we may have the opportunity of seeing for ourselves.

12. Take a round pasteboard box (or make one if necessary), such as chocolate is sold in, and the deeper the better.

Paint the whole inside black, except a white ring on the bottom of the box, and cut one slit in the side, as at A, Fig. 3, and another wider one in the bottom, passing through the centre. Through this last, push a piece of flat smooth glass, such as a window pane or the glass of a picture, B C D E, Fig. 3. It is convenient to have the bottom moveable, so that

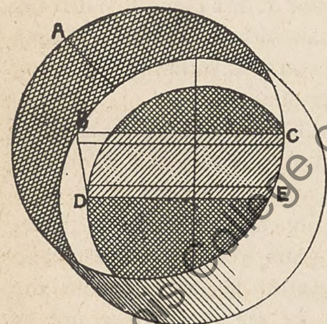


Fig. 3.

[1] Reflected, from the Latin *re*, again, and *flecto*, I turn, a ray returned or thrown back.

you can bring the side slit opposite to any part of it at pleasure.

Now hold the box in the sun[1] so that the sunshine may come through the side slit and throw a beam of light upon the blackened paper. Where the sunbeam strikes the glass you will find that it is divided into two unequal parts, one passing on through the glass in nearly the same direction as before, and one reflected upwards from the surface. It is possible that at first you may have a little difficulty in distinguishing the reflected ray, so faint is it in comparison with the other. If this is the case, shade the front of the box so that other light may not reach it, move it a little from side to side, as there is more chance of detecting a faint ray when it is moving, and if the bottom is moveable turn the slit nearer to the glass, so that the light may fall more obliquely upon the reflecting surface. When you have found the reflexion you will probably observe that it is double, consisting of two rays of which the upper is the brightest. One of these is reflected from the upper, and one from the under side of the glass.

In this chapter we have to examine that part of the light which passes through,—that which is reflected will be considered afterwards.

13. Most of the transparent media with which we are acquainted are different in density; that is to say, some are more solid and close packed than others. When any substance expands with heat there does not

[1] Sunshine is preferred for this experiment since the great distance of the sun causes its rays to be practically parallel to us. Ordinary artificial light is confusing on account of its divergence.

come to be more of it than before: its weight is just the same, but its particles are not so closely packed together, and so it takes more room; its density is less. Even at the same temperature there are some things which are denser than others, that is to say, which have more particles in the same space. Glass is denser than water, water than air, cold air than hot air. In measuring density it is convenient to take water as the standard and call its density 1; then we call the density of glass more than 1, and of wood less than 1.

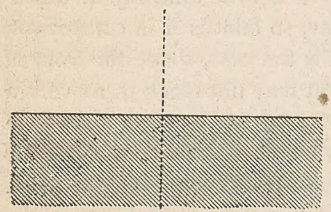


Fig. 4.

14. When a ray of light passes from one medium into another of different density, unless it falls exactly perpendicularly on the fresh surface, it will be bent, or *refracted*,[1] out of its original direction. If it falls perpendicularly so that the ray makes equal angles in all directions with the surface (Fig. 4), it will pass straight on without any bending, but if it falls obliquely so that it make unequal angles with the surface then it will not pass straight on but will be bent. If it is passing into a denser medium it will become more perpendicular than it was to the surface it enters, if into a rarer or less dense medium it will become less perpendicular to the surface than before.

15. To observe this conveniently, take up the

[1] *Refracted*, from the Latin *re*, and *fractum*, broken, a ray broken back.

round box again, and upon the white ring left in the bottom mark the degrees of the circle, drawing a conspicuous line right across the circle, passing through its centre at right angles to the surface of the glass. This we will call the perpendicular line.

Take out the glass while doing this, and before restoring it to its place hold the box for a moment in the sunshine, letting the sunbeam through the slit cross the *centre* of the circle, and observe the degrees where it crosses the white ring. The beam is perfectly straight, its lower extremity being at the same distance from one end as the slit is from the other end of the perpendicular line. Now replace the glass in its position, and let the beam fall as before upon the centre of the circle. The beam is no longer straight throughout its course. That end of it which has passed through the glass has moved nearer than before to the perpendicular line. It has become more perpendicular to the surface of the glass—glass being a denser medium than air. The amount of bending depends on the thickness of the glass, and as with thin glass the refraction is so slight as to be hardly perceptible, the thicker the glass the better for this experiment, provided always that it has smooth parallel sides.

If the bottom of the box is not moveable, cut another slit to admit the light opposite to one end of the perpendicular line, and thus satisfy yourself as to whether light is refracted when it falls perpendicularly on the surface of the glass.

CHAPTER III.

REFRACTION—*continued.*

16. Having thus convinced ourselves of the reality of the refraction, we shall find it more convenient for the present to examine its laws by means of diagrams.

If A B X Y, Fig. 5, represents the thickness of a flat piece of glass, and C D a ray of light falling obliquely upon the surface of it, let us draw a line perpendicular to the surface where the ray touches it, as E F, and

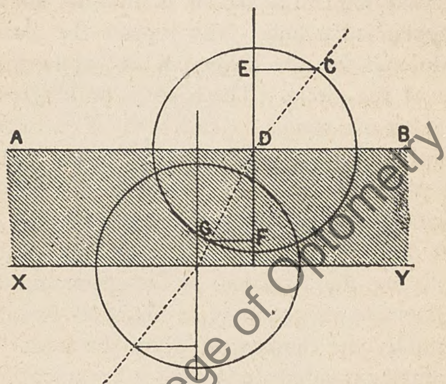


Fig. 5.

notice the size of the angle which C D makes with E D. This angle C D E is called the *angle of incidence.* Now as the ray is passing from air into glass, that is from a rarer into a denser medium, we know it will become more perpendicular to the surface of the glass than it was before, and be bent somewhere in the direction D G, making a smaller angle with the line E F than it

did in passing through the air. This angle G D F is called the *angle of refraction*, being evidently a smaller angle than the angle of incidence. Now, when the ray reaches the other side of the glass it will come again into a less dense medium, and consequently will be bent away from the perpendicular line. Accordingly, let us draw another perpendicular line, and make the ray incline to it at a larger angle in the air than it did in the glass.

But the question is, and a very important one too, how much larger or smaller these angles are to be made? In order to answer this we must first learn to measure the angles.

17. The ordinary way of measuring angles is to ascertain how many degrees of a circle they contain. But in the present case we must adopt another method of estimating angles.

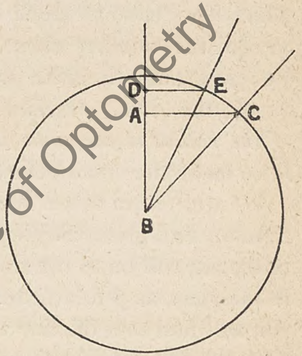


Fig. 6.

Let A B C (Fig. 6) be the angle we have to measure. Draw a circle of any size with the point B as its centre, and join A and C by a straight line at right angles to A B. In this example, the line B C, which is a radius of the circle, may be divided into eight equal parts, and the line A C will then contain five of the same sized parts: therefore the length of A C is $\frac{5}{8}$ of the length of the radius B C. Now this fraction, $\frac{5}{8}$, is called the

sine of this angle. It does not matter whether the equal parts be inches or miles—if the proportion of the two lines to each other be as five to eight—if the sine be $\frac{5}{8}$—the angle, that is the inclination of the two lines to each other, is always of the same size as this.

Now if the line B C be supposed to be a moveable pointer, swinging round on a pivot at B, like the hand of a watch, we may by bringing it nearer to A B make an angle whose sine shall be $\frac{3}{8}$; that is to say, the length of the crossbar will be $\frac{3}{8}$ of the length of the pointer or radius—D E, E B (Fig. 6), and comparing this with our first angle we should say, the sines of the two angles are to each other in the proportion of $\frac{5}{8}$ to $\frac{3}{8}$, or (since the length of the radius 8 is the same in both) in the proportion of 5 to 3. Thus, if we have an angle with a sine of $\frac{5}{8}$, and desire to construct another whose sine shall be $\frac{3}{5}$ of the first, we have only to make the crossbar of the second $\frac{3}{5}$ of the first, *provided always that the length of the radius is the same in each case*; that is to say, if we make the circle the same size in both cases.

We will return to our ray of light. If it be passing from air into glass, the sine of the angle of incidence, in the air, will be to the sine of the angle of refraction, in the glass, as 3 to 2 nearly. Looking back to Fig. 5, you will find that the line F G is $\frac{2}{3}$ of the length of the line C E: they are both drawn to the same length of radius, for D C and D G are radii of the same circle, and all radii of the same circle are equal in length.

18. Different transparent media vary very much in the amount by which they bend or refract the rays passing into them. The standard by which they are

measured is the amount of bending undergone by a ray passing into them from vacuum, that is, from space devoid of air or any other refracting medium. Thus, when a ray is passing from vacuum into water or *vice versa*, the sine of the angle of incidence and the sine of the angle of refraction are to each other in the proportion of nearly 3 to 4, or exactly as 1 is to 1.335. Hence, this number, 1.335, is called the refractive index of water. In the passage from vacuum into air, the proportion of the sines is 1 to 1.000294, or nearly 3401 to 3402. Hence, 1.000294 is the refractive index of air. The refractive index of crown glass is 1.52, and of flint glass 1.55, both of which give nearly 3 to 2 as the proportion of the sines of the angles made by a ray passing into them from vacuum.

We have, therefore, the following table. Longer lists of the refractive index of other transparent bodies will be found in more advanced text books:—

Refractive index of air,	...	...	1.000294
,, water,	...	...	1.335
,, crown glass,		...	1.52
,, flint glass,		...	1.55

These are called the *absolute* indices of refraction for these media, being all measured by a common standard—the passage of rays from vacuum.

19. To get the refractive index when the ray passes from one of these media into another, we must measure the sine of the angle of incidence (which we will call *sin i*), and divide it by the sine of the angle of refraction (*sin r*); thus $\frac{sin\ i}{sin\ r}=$ index of refraction.

20. A simple experiment will make the whole

matter clearer. Take a tin biscuit box (the 2 lb. size), A B C D Fig. 7. Mark a scale of inches along the bottom of the box, place it in the sunshine, and note where the edge of the shadow falls, A E. Now without moving it, fill it with water to the brim, and note where the shadow falls again, A R. Pour

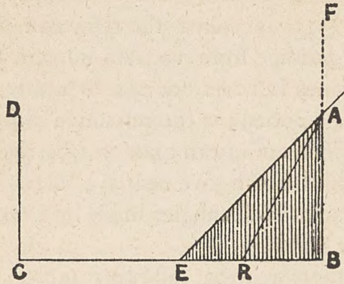


Fig. 7.

away the water, and measure accurately the distance from the edge of the box A first to E, and then to R.

Now in the first case, when the box was empty there was obviously no refraction at the surface of the box, and therefore the angle B A E below the surface must be the same as the angle of incidence S A F above the surface, and the sine of incidence will be expressed by the length of B E divided by that of A E—or $\frac{BE}{AE} = sin\ i$ (17).

In the second case, refraction having taken place at the surface of the water, the angle B A R is the angle of refraction, and $\frac{BR}{AR} = sin\ r$.

However much the slant or obliquity of the inci-

dent ray may vary, these two fractions $\frac{BE}{AE}$ and $\frac{BR}{AR}$ will always bear the same proportion to each other, and consequently, whatever their values may be in figures, when one is divided by the other, the quotient is always the same, and this quotient is the refractive index for the passage of rays from air to water.[1]

When we know the absolute refractive indices of the substances, we can find from them their relative refractive index. We find that the refractive index of water is 1.335, and of air 1.000294, that is nearly 4 to 3, so the sines of the angles in water and in air must be to each other nearly in the proportion of 4 to 3. And since we know that the smaller angle will be in the denser medium, it follows that the sine of the angle in water will be about $\frac{3}{4}$ of the sine of the angle in air. You will notice that these numbers are taken backwards, and the refractive index of air becomes the sine in water, and the index of water the sine in air, and may remember as a general rule that the sines in any two transparent media are the refractive indices of the media reversed. The proportion of the sines in air and glass (1.000294 and 1.55) are nearly 2 to 3, and in glass and water (1.55 and 1.335) nearly 7 to 6. These numbers are easier to deal with and sufficiently accurate for our present purpose.

21. One thing more must be taken into account before we rest and recapitulate what we have learnt. In drawing these figures on a piece of paper, there is no difficulty in knowing in which direction the ray will be bent, by the rules given in this chapter, because the lines must

[1] This is Kepler's method.

all lie on the flat surface of the paper; but supposing we are dealing with a thick cube of glass, that is a piece which is equal in length, breadth, and height, a little consideration will show that an oblique ray falling on the top of it might make its change of path into more than one direction, and yet keep the right proportion between its angles. We do not know which surface it would come out upon. The truth is, that the two angles must be both in the same plane. A ray, being only a single line, may be in any plane, but an angle between two straight lines can only be in one; so, find the perpendicular by setting a pencil upright on the glass, just where the ray touches it, and these two lines together, forming the angle of incidence, will determine the plane.

22. This subject of planes is not easy at first, and it will be well worth while to give it a few more words of explanation. A plane means a flat surface, and those points are in the same plane which could be all touched by one flat surface. A single point cannot determine a plane, for it may belong to many. The walls, floor, and ceiling of a room are all planes, and the point of the floor in the corner of the room is in the plane of the floor and of two of the walls all at once. Neither can a straight line fix a plane; the upright line in the corner of the room belongs equally to both walls, or the line along the top of the room belongs equally to the wall and ceiling. You can cut an orange in many planes, and yet lay open the central line of the core. Two straight lines, or a line and a point, or any three points which are not in a straight line, are therefore necessary to determine a plane.

With the upright line in the corner of the room, take a spot on one of the walls, and then you fix a plane immediately.

Now, to go back to our cube. The refracted or bent ray must be in the plane determined by the line of the ray falling upon the cube, together with a line perpendicular to the surface resting on the point where the ray falls. Suppose your cube, instead of being of hard glass, was of soft, clear jelly. If you could bring the edge of a knife down upon its upper surface, so that the blade of the knife just touches both the ray and the middle of the pencil that was set upright on

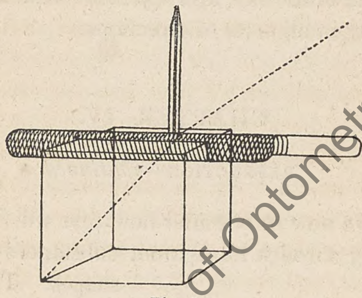


Fig. 8.

the spot where the ray touches the jelly, and cut down through the cube, keeping the knife in the same position (see Fig. 8), then on the fresh cut surface you would find the refracted ray.

We can now go over and sum up the laws of refraction.

23. 1st. The angles of incidence and refraction must be in the same plane.

2nd. The sines of incidence and refraction always

bear the same proportion to each other in the same two media.

Before going further, it would be well to practise drawing the refraction of rays more or less oblique in different media, according to the proportions given in the table in this chapter. They cannot be drawn with mathematical accuracy; pens and pencils will not do it. But it may be done sufficiently nearly to make the student thoroughly accustomed to angles of incidence and refraction, so that he may not have to stop and puzzle over them on coming to them in future. Try the refractions out of denser into rarer media as well as the other way, and try them with the incident ray coming in all sorts of directions.

CHAPTER IV.

REFRACTION—*continued.*

We have now to consider how rays will be affected by passing through transparent substances of definite shapes. The simplest example, and that upon which we have already experimented, is a piece of clear glass having smooth parallel surfaces—in fact, a good window pane.

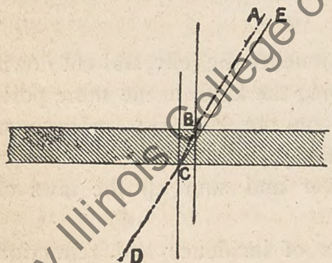


Fig. 9.

24. We now know perfectly well what will happen to a ray falling obliquely upon a

smooth surface of glass; it will be bent as at B in Fig. 9. What will happen to it when it reaches the other side of the glass? It has now to pass from the denser medium of glass back to the rarer medium air, so we must draw a fresh perpendicular line at C where the ray falls upon the fresh surface and construct our angles according to the ordinary rules given in the last chapter. We shall find the new direction of the ray C D to be parallel[1] to its direction *before* it entered the glass. How far apart the parallel rays are depends on the thickness of the glass.

25. Now, what is the practical consequence of this? We learnt in the first chapter that we can only *see* things when rays of light come from them into our eyes, but that we do not see the rays, only the objects which send them. Now, if the ray should get bent about ever so many times on its way to us, we cannot see all that bending about; yet though we do not see round corners, still the ray reaches us at last, and shows us the object it came from; and what is the consequence? This—that *we always see an object in the direction along which the ray came last.* For instance, looking back to the last figure, if your eye were at D and the flame of a candle at A, you would be able to *see* the candle, for the ray coming from it to B would be bent to C and finally reach your eye by the road C D, but the candle would not appear to be at A, it would look as if it were along the line C D which the ray travelled last; consequently as you could still judge its dis-

[1] Parallel. Two lines are said to be parallel to each other when they remain equally distant throughout their course.

tance fairly, it would look as if it were at E, a little aside from its true place.

26. If you look through a window then, at any objects from which the rays reach the window pane obliquely, you will see them all a little aside from their true place; though as they are all moved aside equally, or nearly so, they look tolerably right. But supposing that the surfaces of the glass are not quite smooth, or that the glass is not equally thick throughout, or that different parts of the glass are not of the same density, you probably now know theoretically as well as practically what will be the consequence. Everything seen through it will be very unpleasantly distorted; the rays coming from parts of the same object may take quite different journeys according to the irregularities of the glass, and so present to your eye a picture having very little resemblance to the truth. In that case the only remedy is to open the window if you want to see the view; the rays from the objects around you will then come without being bent or refracted.

It is very possible that you may never have noticed that everything seen obliquely through glass is displaced a little to one side, partly because in our ordinary window glass the displacement is very small, and partly because the wooden frame in which the panes are set prevents the eye from directly comparing what is seen through the glass with what is seen through the open window; but if you lay a piece of rather thick glass on the page of a book, so that it partly covers the printing, and look at the page obliquely, the displacement will be very apparent.

27. Let us see the bearing of this important rule—that we always see objects in the direction along which the rays from them came last—upon the statements in the last chapter.

We know that a ray obliquely incident on water, as A B (Fig. 10), will be refracted to C, but it is equally true that a ray coming from C will be refracted at the surface of the water in the direction B A, and consequently an eye at A will see an object at C along the line A B, which will make it appear to be at D.

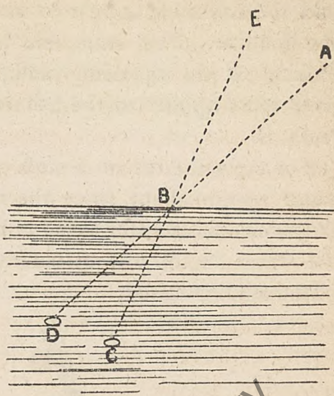


Fig. 10.

28. Place a shilling in the bottom of a tumbler, and pour in water gently so as not to move the shilling. When looked at obliquely the apparent position of the shilling will rise higher and higher as the water rises in the glass. It will still appear to rest on the bottom, because the apparent place of the bottom of the glass is equally raised by the refraction, but if the eye is so placed that the edge of the tumbler, when empty, just conceals the shilling, the appearance of the shilling will rise into sight on pouring in the water.

For this reason rivers appear shallower than they really are when looked at obliquely from the banks, because the apparent place of the bottom is raised by refraction.

Now, transferring the eye to the bottom of the river, let C (Fig. 10) represent a fish. Where will it see a man standing on the bank at A? Both the man and the bank will appear to be at E, being seen along the line CB. The same effect will be produced on looking at the opposite bank, and consequently a river must appear to the fish to be narrower than it really is.

For the same reason a stick plunged obliquely into water appears bent, since the rays from that part of the stick under water being refracted at the surface of the water on the way to our eyes, the apparent place of the stick is raised.

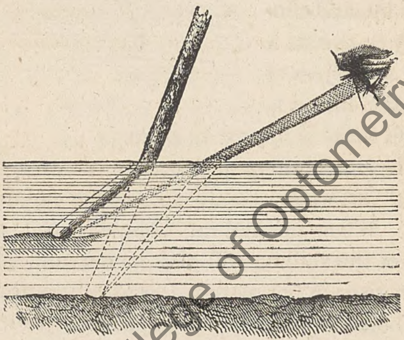


Fig. 11.

29. Another curious effect of refraction is the apparent delay for a short time of the setting of the sun and stars. Just as we were able to see a shilling by means of the water refraction, even though it was behind the edge of the tumbler, so we are able to see the setting stars by means of atmospheric refraction, even when they are below the horizon. Were there

no atmosphere, the star would be out of sight, but the refraction of the earth's atmosphere, which is densest nearest the earth, raises its apparent position over the edge of the horizon, and keeps it for awhile in sight, exactly as the apparent position of the shilling was raised over the edge of the tumbler by the water.

30. Did you, when trying the exercises on refraction, happen to light on one very curious case, in which you could not find out, according to rule, where the ray would go next; it did not seem as if it would go any where? Perhaps you have already discovered this; if not, it is time it were pointed out.

We have learnt that when a ray passes from one medium into another less dense, it becomes less perpendicular than before, *i.e.*, it has to make a larger

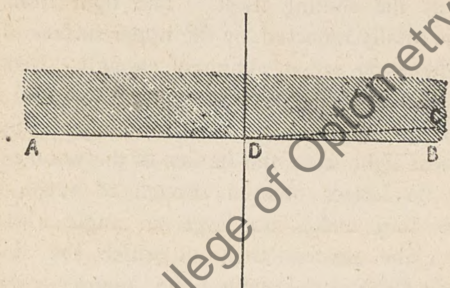


Fig. 12.

angle with the perpendicular than it did in the dense medium. Now it may happen that the ray is so oblique already that if it becomes more oblique in its proper proportion it cannot get into the other medium at all. For instance, if A B (Fig. 12) is the lower surface of some dense medium, such as glass, and a ray such

as C D fall upon it: then if you draw the perpendicular and try to construct the proper angle for the ray to come out of the glass again, you will find that you cannot make it at all, for the sine of the angle would have to be larger than the radius to which it is drawn, which is impossible. In this case, the ray never will get into the other medium: *it will not be refracted at all*, but will all be reflected from the upper side of the surface A B.

31. To see this phenomenon,[1] try the following experiment:—Put a shilling into a glass of water and tilt the glass to one side, then holding it a little above the level of your eyes and looking up through the water, you will see the image of the shilling at the top of the water looking as solid and distinct as the shilling itself. The light from the shilling is totally reflected by the upper surface of the water, when you see it obliquely enough. Now lift the glass gradually higher above your eyes and at a certain height the shilling will suddenly disappear. The rays of light from the surface of the water to the eye are no longer oblique enough to cause total reflexion—they make too large an angle with the surface. The precise angle at which the shilling appears or disappears is called the *limiting or critical angle*, and varies in media of different density. The limiting angle for water is 48½° from the perpendicular.

It will be a good exercise to take a sheet of paper and draw this angle, so as to make yourself accustomed

[1] *Phenomenon* is simply the Greek word for appearance, it is a convenient and frequent scientific expression.

to its size. The limiting angle for glass is 41° 48′; compare these two.

32. Now, suppose we have a number of transparent plates, of gradually increasing density, laid closely one over another with the densest at the top and the rarest or least dense at the bottom, what will happen to a ray passing through them?

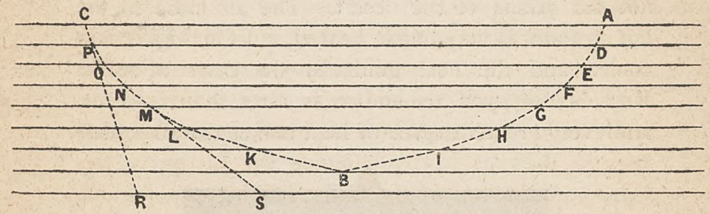


Fig. 13.

Let Fig. 13 represent such a series of plates, and let the ray enter at A, passing through to D; there it will come upon the surface of a rarer medium, and will become more oblique than before; the same will happen at E F G H and I; each plate is rarer than the last, and so the ray becomes more and more oblique at each refraction. But when it reaches B it is so oblique that it cannot emerge into the next layer at all, as we saw in Fig. 12. What becomes of it? From B it is all reflected in the direction B K, and there striking the surface of a denser medium it will be refracted to L, becoming less oblique than before; as it proceeds on its journey through M N O P, it becomes less oblique at every change to the denser medium, till it arrives at C, where you will find that it

has described a very complete curve from its starting point A.

If a candle were at A, and your eye at C, where would you see the candle? You would see it along the last line by which the ray came to your eye, that is along the line CP, and the candle which is at A would in this case appear to be somewhere about R.

33. This deceptive appearance is illustrated on the hot flat plains of the desert. The air close to the hot ground is very much heated, a little higher it is cooler, and the heat gradually decreases upwards. Now, hot air, you remember, is rarer than cold air, and every greater degree of heat makes the air a little

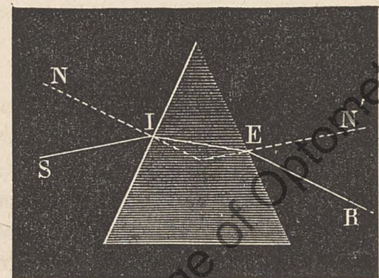


Fig. 14.

rarer, so that in the air over the heated desert you have a medium becoming gradually denser as you go upwards, like the transparent plates in Fig. 13. In the place of the candle A there will be clear sky, and a man whose eyes were at C would seem to see the clear sky lying on the ground at R looking like water: or if you imagine him at N, the appearance of water would be

seen at S. This phenomenon, which is called mirage, is constantly described by travellers in the desert.

The quivering of heated air, which children call the heat dancing, may be frequently observed over the fields in summer. The constant change in refractive power of the air at any one point, as the currents of heated air rise irregularly into the cooler layer next above, causes constant slight shifting of position in the objects seen through it. The same effect is often seen in church, on looking at a window through the heated air rising from a gas lamp.

34. Let us next examine the transmission of light through surfaces that are flat, but not parallel. The application of our rules will show us that the ray entering the glass at I, Fig. 14, ought to leave it again in the direction ER. Now, let us see how this is in actual experiment.

If you can shut the shutters of a room into which the sun is shining, and make a small hole in the shutter to admit a sunbeam, you will have no difficulty in seeing its path traced out upon the dust of the room, till it rests upon the floor, making a bright illuminated spot. Now, in order to observe the refraction, place a prism[1] of glass in the path of the beam. The beam is now refracted, and bent aside, so that we find the bright spot at some distance from its former place. But the bright spot has undergone a wonderful change. Instead of a little round white spot, it has become a long-shaped bright place,

[1] Prism. By a prism is meant any transparent substance, having two sides inclined towards each other; but to show these colours the sides of a glass prism must not enclose a greater angle than 83°.

coloured like a most beautiful and vivid rainbow. The lowest end, which is nearest the spot where the white, unrefracted light fell, is a rich crimson, and the colour passes upwards into orange, yellow, green, blue,

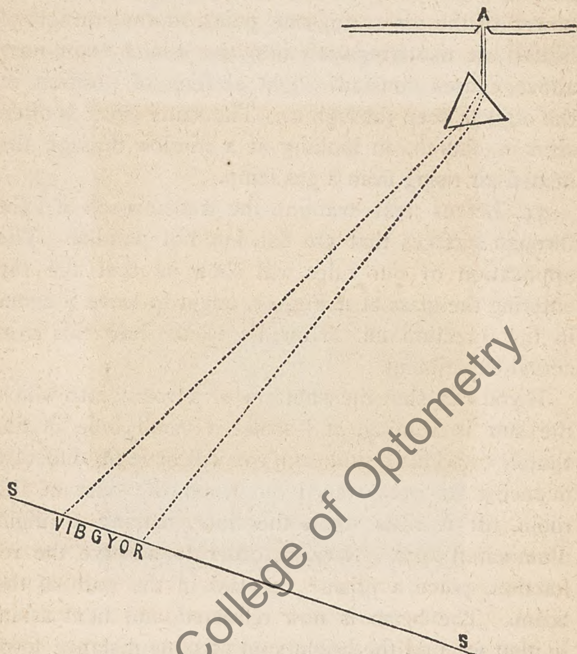


Fig. 15.

indigo, and violet, which is the uppermost. These are indicated by the letters ROYGBIV in Fig. 15.

The simple three-sided prism, Fig. 16, is the best for observing prismatic refraction, but if this cannot easily be obtained, a cut glass stopper, or any piece of

glass with sharp angles may be used to observe the colour.

35. Here, then, is quite a new phenomenon. The prism in refracting the ray has decomposed it,—split it up into many parts, and we find that the white beam was made up of all these beautiful coloured rays. These are actually so many different rays, composing

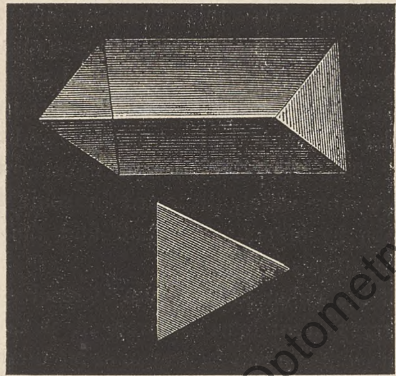


Fig. 16.

what was apparently one, and the reason that the prism has made them visible, is that these rays are differently refracted; they are said to possess different refrangibilities; the red is the least refracted or nearest to the spot where the light fell before; the violet the most refracted or furthest from it, and the rays between these two are refracted at every intermediate angle. You might turn the refracting prism into any other direction, so that the coloured band would fall in different places, but you would always find the red

end of it nearest to the original or unrefracted path of the light, and the violet furthest from it. The coloured band of light is called the prismatic spectrum, and this one is known as the solar spectrum, because it is the sun's light that we are examining.

It is plain now that the rules which we have learnt for determining the refraction of light cannot apply to the whole of these rays, for they are all refracted at different angles. This rule therefore only shows us the place of the mean or middle of these rays.

36. The refrangibility of the coloured rays differs in different media, but the order is always the same; namely, the red end is the least refracted and the violet the most. The spectrum is longer, in other words the colours are more widely dispersed by some refracting media than by others. We shall find the practical importance of this fact later.

Now if the coloured spectrum is received upon a suitable transparent lens, so arranged as to bend all the rays together again in transmitting them, a piece of paper held at the point where they all meet again will receive just such a white spot as fell on the floor at first before the prism was put in the way; but by intercepting some of the coloured rays on their way, you can change this spot to all manner of different colours; and there is no colour that we are acquainted with that may not be obtained by stopping out some or other of the rays of the solar spectrum, thus showing that the compound white light that comes from the sun is able when split up to produce all the various colours we see in the world round us.

37. The violet seen at the end of the spectrum

beyond the blue may possibly be an indication of the beginning of a new band of rainbow colours out of the range of our human vision, just as in the musical scale the end of one octave is the beginning of a second. The blue corresponds to the higher note in an octave, the red to the lower, and the pitch rises from one to the other.

The rainbow itself is an effect of the refraction and reflexion of sunlight by drops of water, either in rain or in a waterfall.

In this chapter we have just opened the door to investigations of endless interest and beauty. We have not touched at all the most wonderful revelations made to us through the solar spectrum, nor mentioned the interest to be found in the spectra of other sources of light besides the sun. The spectroscope is an instrument fitted with prisms for investigating different spectra. It is impossible here to do more than just indicate these things, and then go on with the subject of refraction; but we will return later to this subject and enquire what news is brought to us from the distant sun and stars by their swift-footed messenger Light.

CHAPTER V.

REFRACTION—*continued.*

The next thing we have to consider is the behaviour of rays of light falling upon curved transparent surfaces. The law for their refraction remains the same as before, dependent on the angles they make with

a line perpendicular to the surface; but the difficulty in this case is to be sure what is perpendicular to the surface at any point.

38. When a curve is part of a circle, a line drawn from the centre of the circle to any part of the circumference is perpendicular to the curve at that point. But when the curve is not part of a circle we must seek another method of determining the perpendicular.

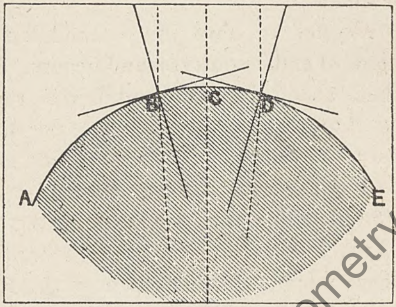


Fig. 17.

Let A B C D E (Fig. 17) be a curved surface with parallel rays falling upon it at B, C, and D. Draw a straight line outside the curve, which shall just touch the curve, but without cutting through it, at the point B where the ray falls. Such a line, touching a curve without cutting it, is called a tangent, from the Latin *tangere*, to touch. Now, a line drawn at right angles to the tangent and passing through the point B is the perpendicular to the curve at that point. You can easily measure the angles made by the ray with the perpendicular, and find

its new direction on the other side of the surface. You will find that it is bent inwards towards a line passing through the centre of the curve. Exactly the same will be the case with the ray falling on D; the tangent and the perpendicular are drawn, and this ray also is found to be bent inwards towards the same line. The ray at C is perpendicular to that point of the surface, and therefore passes straight into the glass without refraction. If any more rays parallel to these fell upon the curved surface between B and C, and between C and D, they also would all be refracted towards the centre line, and would meet and cross there, afterwards getting farther and farther apart again, as shown in Fig. 18.

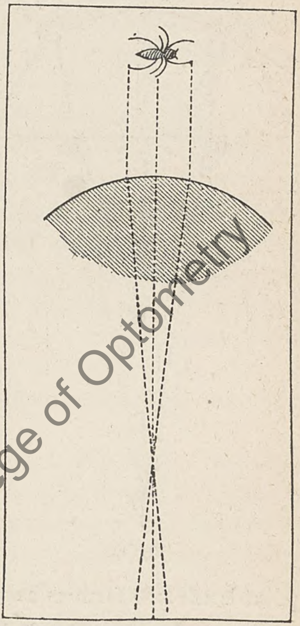


Fig. 18.

Every ray of light brings with it an image or picture of the point it comes from, and if a bundle of rays fall upon the curved surface from the same object—a little spider, for instance—and the rays are so refracted by the surface that they all meet and cross on the same spot, then if you could place your eye just at that meeting spot,

which is called the *focus*, you would receive a ray of light from every point of the spider at once, and so see the whole spider clearly.

But as it is impossible to place your eye inside a solid block of glass, we must give our curved glass another side or surface in order to get the rays of light out into the air again, and this fresh surface with the fresh refractions it causes will make some difference in the direction of the rays.

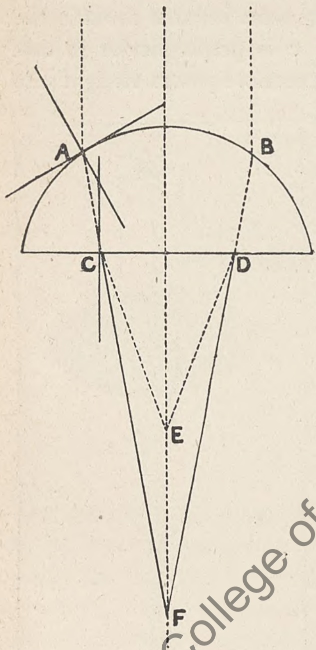


Fig. 19.

39. Suppose we first try the effect of making the second surface flat, as in Fig. 19. A glass with one or both sides curved is called a lens, and the name of this one is a plano-convex lens, because one side is flat or plane, and the other has a convex curve—that is a curve whose middle point is the one farthest away from the other side.

In Fig. 19 the parallel rays falling on the curved side at A and B are first refracted to C and D, where they meet the second surface. Find the perpendiculars to this surface, and the fresh refractions,

remembering that the angles must be larger in the air than in the glass. You will discover that the side rays will now be bent still more to the central line than before, and consequently will meet or come to a focus at E, whereas if the second side of the glass had not come between they would have met at F. The effect, then, of the second side is to bring them to a focus more quickly.

40. Hold a common magnifying glass facing the sun, and putting a sheet of white paper close behind it, move the paper gently back from it till you find the distance at which the spot of refracted light is smallest and brightest; this spot is called the *principal focus* of the lens. Be careful with this experiment, or you will presently prove that the lens has converged the sun's heat as well as light upon its focus, by the scorching and burning of the paper.[1]

If you can darken the room, and admit light only through the lens, you may see the light between the lens and its focus in the shape of a solid cone having the focus for its point and the lens for its base. A dark lantern with a converging lens in a dark room will show this as well.

41. There are several forms of lenses in use. No. 1 in Fig. 20 represents a section of a double convex lens, having both its surfaces convex. Then follow the plano-convex and two concavo-convex lenses of different forms: these have one side convex and the other a concave or hollow curve. The fifth lens is plano-concave, and the sixth doubly concave.

[1] White paper is less likely to burn with a burning glass than coloured or dark.

The line drawn through the middle of all these lenses is called their axis, and represents the line towards which the rays would be bent after refraction.

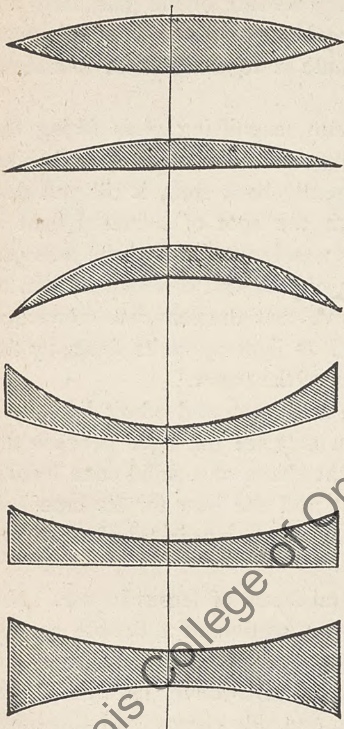


Fig. 20.

No. 1, Fig. 21, is an illustration of the effect of a double convex lens, and No. 2 of a double concave lens upon the direction of rays that were previously parallel. The convex lens makes them converge rapidly, while the concave lens causes them to diverge.

It will be well to make experiments with ruler and compasses on all these lenses, and see what effect their different shapes have on the direction of rays passing through them. Try them with converging and diverging rays as well as with those that are parallel. It will be found that the same lens has more than one focus, according as the rays that fall upon it are parallel,

convergent, or divergent. The point at which a lens converges *parallel* rays is its *principal focus*.[1]

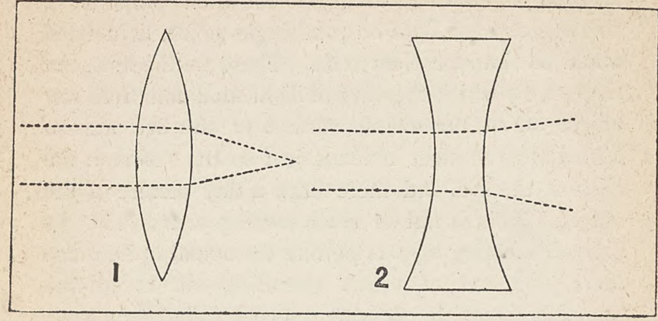
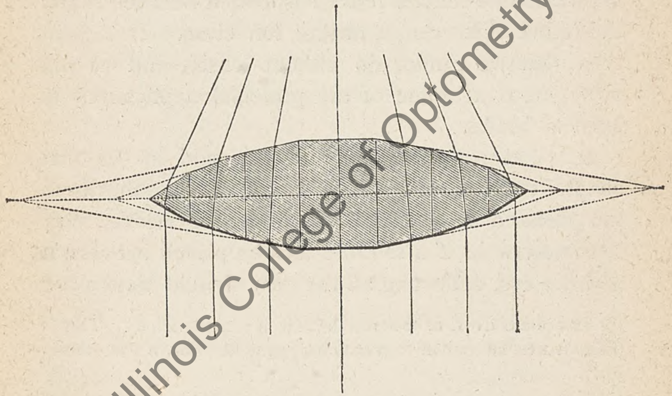


Fig. 21.

[1] Since the amount of refraction of a ray through a lens depends upon the position of the *tangents* at the points where it enters and leaves the lens, the inclination of any such pair of tangents to each



other may be regarded as the inclination of the surfaces of a prism; and thus the whole lens is sometimes spoken of as a series of innumerable prisms, having their refracting angles turned away from

42. Meanwhile let us ask: What is the practical value of these lenses? Well, first there are lenses of such importance, that, but for their property of bending rays of light on to a single point, light itself would be almost useless to us. These are the lenses of the eye, by which the rays of light that fall from any object on to the visible surface of the eye are so refracted as to meet in focus just on the retina at the back of the eye, and there draw a tiny picture of the object. This is not so much putting your eye at the focus of meeting rays as putting the actual optic nerve there, one end of which spreading out in minute branches forms the delicate network called the retina, while the other end is in the brain.

43. The curved eyeball itself, which is full of transparent liquid, first refracts the rays, but there is a tiny double-convex lens[1] suspended between it and the retina which causes further refraction. It is clear, then, that we cannot do without lenses, and we will now glance at some of the principal applications of artificial lenses.

44. You may remember it was said in the first chapter that a star so distant that its light reaches us in too diffused a condition to render it visible, may become visible if a suitable lens be placed between it and the eye, collecting all the rays of light that reach

the axis in a convex, or towards the axis in a concave lens. This is presented to the eye in a greatly exaggerated form in the accompanying figure.

[1] If you can get a sheep's eye and cut it open, you will find this lens inside, and if you hold it up to a candle, and place a sheet of white paper behind it, you will get an image of the candle on the paper.

the larger artificial lens, and so bending them as to concentrate them on the smaller lens of the eye. An artificial lens, then, can bring within the range of sight objects too distant to be seen by the naked eye.

45. But it can also render visible objects which are too small to be seen by the unassisted eye, and that in this manner. To return to our friend the spider. The small black spider in Fig. 22 is the object behind the lens. For the sake of clearness, only three lines are given as specimens of the rays of light that fall from it on the lens. They will, as we have already seen, be so refracted as to meet on the point B. *But things always appear to be in the direction along which the rays from them last reach our eye*, and consequently to the eye of an observer at B, the

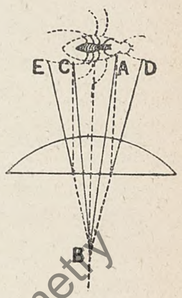


Fig. 22.

spider's front leg will not appear to be at A but at D, and his hind leg not at C but at E; the same will be the case with the intermediate refracted rays, so that the spider will appear to occupy a much larger space than it really does, and will look the size of the dotted spider. This larger image will be a true likeness, an enlarged picture of the smaller one, and will enable us to study details that were before too small to be seen.

46. If there were no lens between the spider and the eye, the rays of light from the extreme ends of the spider which meet in the eye would open at a very small angle; they are represented by the straight lines from A to B and from C to B in the figure:

you see that the angle they make with each other is a small one. But the refracted rays make with each other the much larger angle D B E. The magnifying power of the lens consists in the amount by which it can increase this angle, which is called the *visual angle*, or angle of vision.

An arrangement of one or more lenses for producing this effect is called a simple microscope.

CHAPTER VI.

REFRACTION—*continued*.

47. In trying experiments on the refraction of light through different shaped lenses you probably found that though the rays were all bent towards the same centre line, yet they would not all meet on a single spot. In Fig. 23, for instance, the outer rays meet on the point A, and the inner rays on the point B, so that no exact focus can be obtained. This inaccuracy, which is found when the curve is part of a sphere, is called *spherical aberration*,[1] and is remedied by making the curve bulge out more in the centre, so

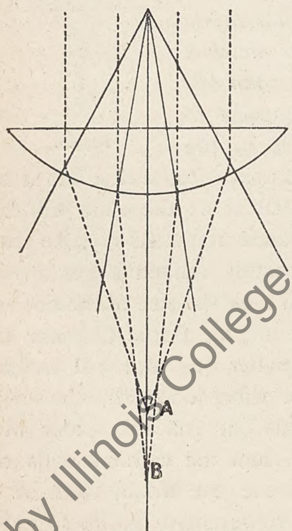


Fig. 23.

[1] Aberration, from the Latin *ab errare*, to wander away.

as to bring the central rays more rapidly to a focus, or simply by excluding the outermost rays. The exact curve which will make the rays from all parts of the object focalise, or come to a focus, at the same point, can be discovered by mathematics, and very great attention has been bestowed on the curves of lenses by mathematicians, till they are brought to great perfection.

48. But there is yet another source of confusion in looking at objects through lenses, and this is the different refraction of the different coloured rays in white light. The effect of this is to produce a ring of colours round the edges of the object looked at. The mixed rays of light falling from the object upon the lens are there differently refracted and divided, but they are so close together that the blue of one falls upon the red of another and the green of a third, so that this remixing produces the effect of white light again over most part of the surface, and it is only at the edges where the coloured rays do not find compensating colours that they are perceptible to us as rainbow fringes.

This confusion of colours at the edges of the object is called *chromatic aberration*, and for some time proved so serious a difficulty that some of the great astronomers abandoned the idea of getting a useful refracting telescope, because of the disturbing fringe of colours always produced, and so used reflecting telescopes instead.

But the difficulty was got over at last.

49. It was said in the last chapter that the spectrum of light was made longer or more widely dispersed by some transparent substances than by others,

and this is found to be the case with different kinds of glass. For instance, one kind of glass may make the length of the spectrum of light passing through it equal to one-thirtieth part of the length of the whole refraction; that is to say, if the light is bent by the glass thirty degrees out of its original path, then the spectrum will be as long as one-thirtieth part of this distance, that is one degree. Now if there is another kind of glass which makes its spectrum one-twentieth part of the length of its refraction, then with a prism of this glass of such a shape as to refract the light only twenty degrees out of its original path, we should get its spectrum also just one degree in length, being one-twentieth part of its refraction. If a prism of the first glass refracted a beam of light thirty degrees to the right, with a dispersion of one degree, and the light were then caught upon a prism of the second glass and refracted twenty degrees to the left, also with a dispersion of one degree, how would the light finally come out? It would come out refracted ten degrees to the right, for the second refraction only undid twenty of the first thirty, but with no dispersion at all, as the second dispersion would exactly neutralize the first. The light therefore would be quite white.

50. The same principle can be applied to other forms of glass besides prisms, and it is found that two lenses, one of crown and the other of flint glass, can be so shaped as, together, to focalise the light on one point, and will then just correct each other's dispersive power, and transmit colourless light. Such a compound lens is called *achromatic* or colourless.

51. We must now return to the experiments on rays passing through lenses of different forms. We have seen already that the effect produced on parallel rays of light by passing through *convex* lenses is to make them converge, or lean towards a common centre line. You must have discovered also that the effect of *concave* lenses is to make parallel rays of light diverge or spread farther from each other. If instead of parallel we take convergent rays, that is rays that already lean towards each other, we shall find that a convex lens will make them more convergent, bringing them together more quickly, and a concave lens will make them less convergent. It may, if it be strong enough, convert them into parallel rays, or even make them diverge. Divergent rays will in like manner be made more divergent by a concave lens, but less divergent or parallel, or even convergent by a convex lens.

52. The focal length of any lens is the distance between the centre of the lens and its principal focus, which you will remember is the point at which it will bring to a focus rays that were previously parallel. For instance, if parallel rays are focalised half an inch after passing through the centre of a lens, that lens is said to have a focal length of half an inch.

We saw with the convex lens and the rays from the spider, Fig. 18, that all the rays carrying the picture of the spider meet and cross at one point, the focus of the lens. Where do the rays go afterwards?

53. They diverge again, crossing each other, so that the ray that was farthest to the right now goes farthest to the left. The rays are still each carrying with them the picture of that point of the

spider from which they came, and as they are still arranged in the same order or position to each other they still make a complete image of the spider all along their course; a smaller image near the focus or crossing point, and a larger and larger one as they retreat farther from it: the image is inverted or upside down because the rays have crossed each other.

An image like this does not throw out a sphere of rays all round like a real object, but only a cone of rays in one direction, so that it can only be seen by an eye in the right direction. But if you do get your eye into the right direction you may see the image, larger or smaller according to the distance from the focus, and you can apply fresh lenses to it, and by these means magnify a small object much more highly than with a simple lens. As some light is lost by reflexion at every fresh refracting surface met by the rays, it is necessary, when many glasses are used, that the object looked at should be highly illuminated.

54. An arrangement of magnifying lenses, which simply increase the visual angle in looking at any object, is, as has been already said, a simple microscope. An arrangement for magnifying an enlarged and inverted image of the object, as explained above, is called a compound microscope.

55. The object glass of an astronomical telescope produces just such an inverted image of the star or other object looked at through it, but the great distance of the stars from the object glass causes their images to be very tiny compared with their real sizes. The image is brought near to the eye, and magnified

in just the same manner as the image in the compound microscope.

NOTE TO CHAP. VI.

56. The *cause* of refraction appears to be simply the difference of resistance to the passage of the light in different media.

57. That resistance is sufficient to cause refraction is shown by a simple and very satisfactory experiment, described by Mr. Tylor in the number of "Nature" for Jan. 1, 1874. He says, "It occurred to me that an instrument made to perform refraction mechanically would be useful in teaching optics, and that such a contrivance would only require a pair of wheels running on a table, into and out of a resisting medium." "Pieces of a thick-piled velvety plush, known as imitation sealskin, are cut out to represent the sections of a thick plate, a prism, a convex, and a concave lens, and glued on to smooth boards. The runner consists of a pair of boxwood wheels, mounted loosely on a stout iron axle, and is trundled across the board." In repeating these experiments, I have found that dry sand replaces the velvet with advantage, as any required resistance can be obtained by increasing the thickness of the sand, and the largest amount of resistance through which the wheels can pass smoothly serves the purpose best as producing the greatest refraction. The sand also has the advantage of retaining the marks of the wheel-tracks. A mould of the shape in which the sand is required to lie should be cut out in pasteboard and laid upon the board, the sand, previously dried, dusted down upon it from a vessel over the mouth of which a piece of canvas is tied, the whole gently smoothed with a smooth book or anything large enough to cover it, and the pasteboard then lifted away. With wheels two inches in diameter, sand between a quarter and half an inch in thickness may be used, provided the board is tilted up just sufficiently to ensure that the wheels shall pass through it.

When the runner strikes obliquely upon such a layer of sand, the wheel that first touches it is first retarded, and the other continuing to run at its old pace pulls the runner round so that it takes a fresh direction. If it is so set moving that it would emerge at the further side of the sand at a very oblique angle to its edge, the wheel that first issues gains so much upon the other that it turns and re-enters the sand before the second is ready to leave it, making in its fresh path an angle of equal obliquity with the edge of the sand. This

illustrates very prettily the phenomenon of total reflexion from the surface of a rarer medium.

By passing wheels of different sizes through a prism of sand we obtain an illustration of prismatic dispersion, the smaller wheels being more refracted than the larger. Mr. Tylor adds, "For the information of any who may wish to reproduce this simple apparatus I may state the dimensions I have found convenient. The wheels may be 1¾ inch and 2 inch, with rounded edges, mounted on a nearly ½ inch iron axle, turned down to ⅛ inch at the ends."

CHAPTER VII.

REFLEXION.

It was said in the beginning of the second chapter that when rays of light fall upon any object, part of them enter the object and part are reflected from its surface. If the substance be transparent, the entering rays are refracted; if not, they are absorbed.

We have seen that by the Law of Refraction a ray of light passing from one medium into another *of different density* changes its direction and makes a different angle with a line perpendicular to the refracting surface, and that this difference of angle appears to be caused by difference of resistance in the two media. But in the case of reflexion, the incident and reflected rays being both in the same medium, we should expect to find that each makes the same angle with the perpendicular. And this is actually the case.

58. It is the *Law of Reflexion* that *the angles of incidence and reflexion are in the same plane and are equal to one another.*

59. Take up again the round box (Fig. 3) showing the reflected and refracted rays. The first thing noticeable is the proportion between the reflected and the refracted parts of the light. When the slit which admits the beam is so placed that the light falls perpendicularly on the glass, the amount of light reflected is very small indeed; but on moving round the bottom of the box so as gradually to increase the obliquity of the incident beam, a larger and larger proportion of light is reflected.

When light passes from air into water, the proportion of rays reflected varies from 20 out of 1000 at a perpendicular incidence up to 725 out of 1000 at a very oblique incidence. It is this great proportion of reflected light which makes the reflexion from the sea more dazzling at sunset than when the sun is high.

60. By simply placing a sheet of white writing paper horizontally before a candle, and gradually raising it to the height of the eye, the increased amount of reflected light is easily observed. When looked at very obliquely, an image of the flame may be seen reflected in it.

We must next observe the angles of incidence and reflexion. It will be well now to change the glass in the box for a piece of looking-glass which will reflect a much larger proportion of the incident light. (From this we see that the intensity of reflexion varies with different reflecting surfaces, even when the angle of incidence is the same.) The double reflected ray will still be seen, but now the lowest, or that from the silvered back of the mirror, is much the brightest.

Every object which does not, like the flame of a

candle, give out light of its own, becomes visible to us by reflected light. We know that it is by the light of the sun shining upon the world that we see the hills and fields and trees which arrest and reflect his rays.

61. Now, there are two different reflexions made by these objects. First, a portion of white light is reflected from the surface, this reflexion being much more considerable and visible in proportion as the surface is smooth and polished, as we may see in water or a looking-glass. Secondly, a portion of the light entering among the particles undergoes a further division.

However solid any object may seem to us to be, its minute particles are not really quite close together, but there is a little, very little distance between them, and each particle has surfaces of its own. When the light gets in among these particles it is reflected backwards and forwards among these innumerable surfaces —it echoes, as it were, to and fro, just as your voice reverberates when you shout in a tunnel or a cave— and some of it is finally sent to the eye.

But the whole of it is not reflected.

62. White light is, we know, compound, made up of many brilliantly coloured rays, and the particles of an object select and choose among these colours, reflecting some and absorbing others. We see a rose red, because its particles absorb the other rays of the spectrum and reflect the red. In its leaves, on the other hand, the red rays are absorbed among the particles, and green light is returned to our eyes. And in like manner everything is at work decomposing the

rays of light, and choosing what to reflect and what to absorb. Not of course that the substance has any power to change its choice. The nature of its choice is impressed upon it by the nature of its structure, so that if we change the structure we shall change the light it keeps and reflects. Thus, copper is red, but if it be finely divided it becomes black.

A white object reflects an equal proportion of all the rays: so do grey ones, but the total amount of light reflected by them is smaller, becoming less and less as the grey gets darker, until finally a perfectly black object, in its blackest or shadowed part, reflects none of the colours.

It is by these differences in the amount and kind of light reflected that the rays are able to bring us pictures of the objects around us. For instance, in the case of the spider spoken of in the last chapter, each portion of the spider's body reflects varying amounts of light, and it is these exquisitely subtle gradations of the myriad rays reflected to our eyes from the spider's body which together give us the impression of the spider.

So, when the spider is seen through a lens, it is the light and shade, the collection of strong and feeble rays, that is bent by the lens, and united into a small and bright, or into a large and dim image.

When a transparent substance such as glass or ice is broken up into a number of small fragments, the light in it is continually reflected, echoed backwards and forwards between the surfaces of the fragments and cannot get through at all, but some of it is reflected as white light; this is the reason why snow or crushed

glass look opaque and white, though they are formed of transparent substances.

63. By means of the first or surface reflexion we see images in the looking-glass; by means of the second, we see the looking-glass itself.

The two reflexions spoken of may be clearly seen in looking at grass on which the sun is shining; bright white light is reflected from the shining blades, as well as the subdued green light by which the colour is seen. A painter will be careful to notice which of these two lights predominates on different parts of any object which he is painting. The high light on anything is the point from which most of the white surface reflexion reaches us, and where it is at all brilliant it will overcome the second reflexion, or local colour, at that point, and must be represented by pure white. In painting a wreath of berries of the black bryony, last autumn, I observed that some of the berries when first brought in had no very high light upon them, but their brightest part was only a space of lighter local colour, rather large in proportion to the size of the berry. But as the berries ripened and became more polished from day to day, the high light became whiter, smaller, and more sharply defined, till at last each berry, at its ripest before it began to shrivel, presented on the light side a minute, bright white picture of the window of the room in which they lay. They became in fact little spherical mirrors, reflecting *regularly* the light which had before been merely scattered round them by their comparatively uneven surfaces.

64. Everything touched by light immediately begins

to reflect light on all the things round it, and as they are all doing the same, these dimmed and partial reflexions constantly sent on from one thing to another, scatter and diffuse the light, subduing the bright direct rays of sunshine into common daylight. The reflexions from clouds and generally from the atmosphere do a large share of this work.

65. Rays of light may be collected and brought to a focus by reflexion as well as by refraction. Let A B, Fig. 24, be a ray falling on a polished concave surface. Draw a tangent, or line just touching the curve at the

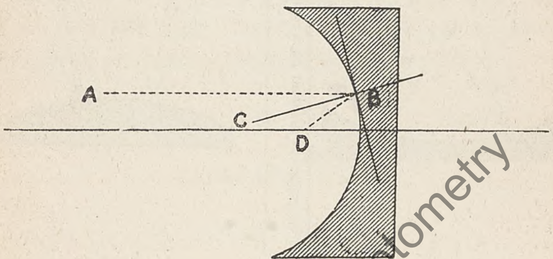


Fig. 24.

point where the ray falls upon it, and a perpendicular to the tangent, as B C. The angle A B C is the angle of incidence, and another angle equal to this must be drawn on the other side of the perpendicular B C, as C B D, for the angles of incidence and reflexion are equal to one another. The reflected ray B D will be found inclined towards the axis of the concave reflector.

In like manner a whole sheaf of parallel rays falling upon a regularly curved concave reflecting surface will all be deflected towards the axis, and if the curve be

suitable they may be brought to a focus upon some point of the axis. Such a reflecting mirror is free from the confusion caused by chromatic aberration, as all the coloured rays, though refracted unequally, are

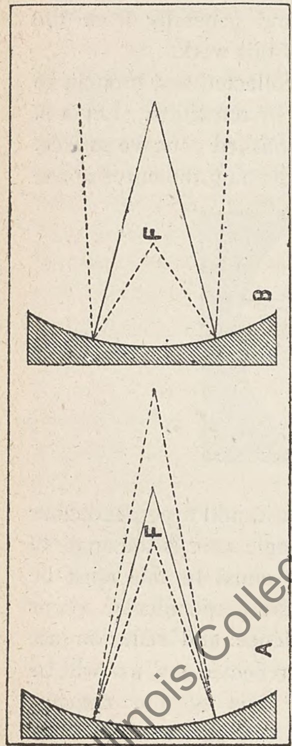


Fig. 25—A, diverging; and B, converging rays incident on a concave mirror; F, focus).

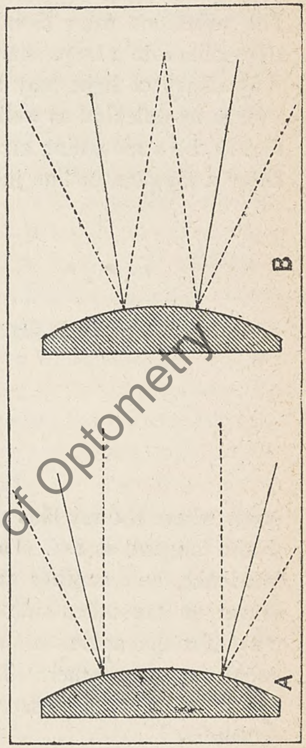


Fig. 26.

reflected equally, and it is therefore sometimes used in telescopes in preference to a refracting lens.

66. Diverging and converging rays may also be

brought to a focus by a concave mirror, more or less quickly. (Fig. 25.)

If, on the other hand, parallel rays are allowed to fall upon a convex mirror, instead of being brought to a focus, they will be widely scattered by the reflector. (Fig. 26 A.)

Divergent rays will be scattered still more widely, but convergent rays may be brought to a focus by a convex reflector. (Fig. 26 B.)

Having now to some extent studied the behaviour of rays of light when they meet with obstacles in their path, we must next inquire what is known about the cause of Light itself. In the next chapter we shall attempt to give an answer to this question.

CHAPTER VIII.

THE UNDULATORY THEORY.

What is Light?

It is time the question were asked.

What is that which, travelling with such inconceivable speed, is employed from moment to moment in delivering its telegraphic communications in our eyes, and exciting in our brain the power which we call sight?

Two only of the theories which have been advanced on the nature of light, need claim our attention.

67. The first, known as the Emission Theory, and supported by the great name of Newton, suggested that extremely minute particles might be given off by

luminous objects, and entering our eyes give rise to the sense of sight, just as fine particles are given out by scented matters, and entering our noses give rise to the sense of smell.

But as the phenomena of light were more closely studied, it was found that this theory could by no means be made to account for them all, and it has given way to the theory now generally held, that light is not matter at all, but motion, an extremely rapid vibratory motion.

68. But if it be motion, what moves? First, the luminous body which emits light. When any substance is raised to such a degree of heat as to become luminous, when it reaches what we call red heat, the particles are in a state of intensely rapid vibration; they are moving backwards and forwards like thousands of minute and active little pendulums.

But something must convey the motion from the luminous objects to our eyes. Is it brought by the air? If so, we should expect to find the motion come to an end and therefore the light to be extinguished on meeting with a vacuum—a place where there is no air. Sound, which is a wave motion in air, is extinguished in a vacuum, yet experiment shows that light will pass freely across it. Nay, look up at the stars. The vast spaces which separate us from them, through which their light passes to us, are not filled with air;—but can empty space either receive or communicate motion?

69. It is assumed—it is necessary to assume—that there is something by the movements of which the waves of light are communicated, and the Undulatory

Theory supposes all space, or at least all that space through which anything is visible to us, to be filled with an extremely fine and subtle substance, penetrating even among the particles of liquid and solid matter. To this substance has been given the name of the luminiferous æther.

Light then, according to the usually received theory at the present day, is a rapid vibratory motion, taking place in an ætherial substance capable of receiving and transmitting motion. The mode of transmission is what we have now to examine, and for this it is necessary to observe wave motions in substances that we can see and experiment upon.

70. When a stone is dropped into still water, it displaces the water, which is for an instant heaped up round the spot where the stone fell. But the water cannot remain heaped up; it sinks again, and thus displaces and heaps up the circle of water next outside it, exactly as it was moved itself by the falling stone; but this circle will not be so high as the first, as the amount of actual displacement is spread over a larger space. The second circle of water sinks in turn and raises a still larger circle beyond, but again to a still less height. This operation is continually repeated, but every time with less elevation until, if the piece of water be large enough, the motion becomes imperceptible, and the whole water has gradually taken the fresh level necessitated by the presence of the stone.

71. Now observe; each particle has in its turn been heaved up for an instant and has then sunk again, and every particle at the same distance from the stone has

been heaved up at the same instant, and sunk at the same instant. The principal motion of the water has been up and down. But what has been the apparent motion to some one looking down at the water? You must have seen it again and again. The spectator saw a circular wave of heaped-up water running out in a larger and larger circle from the stone and becoming continually lower in height :—that is, though the water, we know, rose and fell, yet he saw *something* running away from the stone in all directions. Let us notice this carefully. The wave ran out in circles, while the water moved up and down.

The movement up and down is a vibration, and the extent of the actual movement upwards and downwards

Fig. 27.

is called the *amplitude* of the vibration. The inner circles of water being the most heaped up, their particles rose and fell through a greater distance—they had a greater amplitude of vibration than the particles of the outer circles. As the wave of motion runs out, the moving particles have a continually decreasing amplitude of vibration.

The direction of the movement of the particles is at right angles to the direction of the movement of the wave.

Let A (Fig. 27) be the spot where the stone fell, and B D C part of the circular wave; then the line A D, which is a radius of the circle, is at right angles to the

small line E, which represents the up and down movement of the water.

72. Now let us suppose that the cause of movement in the water is not a single stone once dropped in, but something striking in or upon the water at regular intervals. The first stroke upon the water will send out a circular wave in precisely the same manner as the stone, the second will start another wave in pursuit of the first, the third another, until, if the strokes continue, the surface of the water is chased out into circles of alternate heapings up and depressions, as in the accompanying figure.[1] If the strokes are precisely equal to each other in *force*, then each successive wave will be of the same height in passing over a spot at a certain fixed distance from the centre: for instance, at one foot from the centre every wave that passes will be of one height—at three feet from the centre every wave will be of another smaller height, as the amplitude of vibration of the particles is less at a greater distance from the centre. The particles will rise and fall through the same distance for every wave that passes, and consequently the movement of each separate particle is a perfectly regular seesaw or vibration up and down, faster or slower, according to the length of time between the waves.

Fig. 28.

[1] The water is supposed to be of equal depth throughout, and of considerable extent, and, therefore, free from the complications of motion which arise from an irregular bottom, or, for the present, from reflected waves.

If the strokes upon the water follow each other at perfectly regular intervals of *time*, then the distance from each wave to the next will be equal also; and in this case a line of water from the centre through the circumference of all the waves, will be divided into waves and depressions at precisely equal distances from each other, but with less and less differences of level.

73. The distance from the crest of one wave to the crest of the next is called the *wave length*. If we knew the wave length and the number of strokes

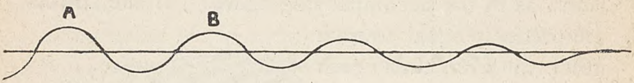


Fig. 29.

upon the water in a given time, we could find the rate at which the waves are running out from the centre.

74. For instance, let us suppose that the wave length (from A to B, Fig. 29) is one foot, and that the number of strokes, or *rate of vibration*, is twenty in a second, then the first wave will have run out a foot from the centre by the time the second starts, that is, in a twentieth of a second. One foot in a twentieth of a second gives us a rate of twenty feet a second for the velocity of the waves.

In like manner, if we know the velocity of the waves and the rate of vibration in the centre, the wave length can be calculated. If the velocity is twenty feet a second, and twenty waves start in a second, it is clear that they will be one foot apart. The rate of vibration also can be reckoned on knowing the wave length and

velocity. If the waves are running at the rate of twenty feet a second, and are a foot apart, then twenty of them must have started in a second. The number of waves that reach the shore in any given time is the same as the number of strokes that started them in that time.

75. Let us suppose the movements to be caused, not by a stroke upon the top of the water, but by something vibrating in the depth of the water. The wave of motion will still run out in the same manner, but it can now flow out equally in all directions, upwards as well as sideways and downwards. The waves are not like rings but globes, not circular but spherical. The outward movement is like that of the film of a soap-bubble which is being blown out larger and larger.

We have now described movements of the same kind as the movements which give rise to light. Every back and forward movement of the luminous particles sends out a spherical wave into the luminiferous æther, and as the vibrations of the luminous particles are equal and intensely rapid, the waves follow each other at regular and extremely minute distances, each particle of the æther making a brief excursion backwards and forwards at right angles to the direction of the wave, like the water particles.

76. But the actual number of such vibrations and size of wave-lengths of light are startling enough. The velocity with which the light waves run out is about 186,000 miles in a second (this number, you will remember, is given for the velocity of light in the first chapter); and the average size of a wave length is less than $\frac{1}{50000}$ of an inch; that is, there are more than

fifty thousand in a single inch. From the velocity and wave length we can calculate the number of vibrations, and the above figures would make it 589,248,000,000,000 in a second.

Before accepting such a conclusion as this, we naturally enquire on what evidence it rests. How is the velocity of light known, and how can the wave lengths possibly be discoverable?

The answers to these inquiries must occupy another chapter.

CHAPTER IX.

MEASURINGS.

77. The first suspicion that light had any measurable velocity, that it was not transmitted instantaneously, arose in the following manner:—

78. Jupiter's moons revolve round him in certain known orbits and in certain known periods, and the three nearest to him are eclipsed by his shadow in the course of every revolution. The time, therefore, at which any one of them will be eclipsed by him and reappear on the other side can be calculated to a second by astronomers, reckoning from any one eclipse. But it was found that the calculated time of this eclipse rarely coincided with the time at which it was actually seen, being sometimes before it, and sometimes after it. This difference, which amounted at its greatest to several minutes, was not capricious, but increased and diminished regularly. Careful observation showed

that the observed time was most in advance of the calculated time when the earth in its orbit was nearest to Jupiter, and lagged most behind when the distance between the earth and Jupiter was greatest; and the Danish astronomer Römer suggested the true cause of the variation, namely, the time occupied by the light in passing across the earth's orbit. The greatest amount of variation is about 16 min. 27 sec. As the relative position of the earth and Jupiter at any given time, and the inclination of the planes of their orbits to each other, are known to astronomers, it only remains to know the actual size of the earth's orbit in order to calculate the velocity of light. This velocity was reckoned by Römer to be 192,000 miles a second, but there has since appeared reason to believe that the size of the earth's orbit was over-estimated, and that the true reckoning is nearer 186,000 miles a second.

79. There is another method of estimating the velocity of light, discovered by Dr. Bradley in the phenomenon called the aberration of light.

[1] Imagine a tube six feet long set upright upon the earth, and a drop of rain falling perpendicularly through it. If the drop enters the middle of the top opening it will fall into the middle at the bottom, as may be easily seen if it is allowed to fall on to a screen which will be marked by its splash. But if, instead of remaining still, the tube is gently and steadily moving forward, then the drop which entered at the middle of the top will fall a little behind the middle at the

[1] This passage is taken almost exactly from Herschel's Lectures on Light, where the explanation is so clear as to leave nothing to be desired by the most unscientific reader.

bottom, because the middle will have gone forward a little, while the drop was coming down the length of the tube. Suppose that on measuring we find that it fell an inch behind the middle, then we may reason in this way. The drop came down 6 feet in the time that the tube moved forward 1 inch, therefore, as there are 72 inches in 6 feet, the drop moved 72 times as fast as the tube. If we know the speed at which the tube moved, we have only to multiply it by 72 to obtain the speed of the drop. We may make sure that the difference is not owing to any slanting in the rain itself, if on moving the tube at the same rate in the opposite direction we again find the drop an inch behind on the other side.

Now, let the tube be a telescope, and the drop of water the light from a star. You will remember that the light of the star is a huge, outrunning spherical wave of vibrations. When the telescope is pointed straight at the star, part of this wave breaks upon the object-glass, the æther in which transmits the vibrations, refracting them so as to focalise the light, and bring it within the range of the eye-glass at the other end. If the telescope were perfectly still, the line along which we see the star, the line that joins the focus to our eye, would point straight to the star itself, and we should see it in its true place. But the telescope is not still. Nothing on earth can be still, while the earth itself is whirling forward in its mighty orbit; and consequently while the light is descending the tube, the telescope itself has moved forward a certain distance. The light still comes straight on, as the drop still fell straight down, but the movement

of the tube makes it appear to fall in a slanting line.

Practically, to us it is not perpendicular, because the movement of the telescope has left it behind. If this presents any difficulty, try the following little experiment :—Take a mounted globe, dip your finger in water, and draw a line with it upon the globe straight from the north pole to the equator; the track of your finger will of course lie due north and south, and parallel to a meridian of the globe. Now, do the same again, while some one makes the globe rotate rapidly towards the east; the wet track will no longer lie north and south, but will be found as a long sloping line lying from north-east to south-west. It has been left behind by the globe, the equator of which rotates more rapidly than the poles, and instead of being parallel to the meridian it will make a considerable angle with it.

In like manner, the movement of the telescope makes the light appear slanting. The line along which we see it no longer points straight to the star, and since we always see things in the direction from which their light last reached us, we no longer see the star in its true place, but a little aside from the centre. Now, the amount of displacement, though small, is measurable, and its proportion to the length of the telescope gives us the proportion of the velocity of the earth in its orbit to that of light.

A difficulty rises here which it may be well to clear away before going farther. How are we to know when the telescope is pointing straight to a star, except by seeing it in the middle of the glass?

As the exact position of any place on the earth is fixed by means of its latitude and longitude, so the exact place of a star in the sky is reckoned by means of a celestial latitude and longitude. With suitable machinery a telescope can be so set as to have its centre directed accurately towards any given spot in the sky, and if a star once seen upon that spot is afterwards found to have moved from it, the amount and direction of its motion can be readily detected.

Now, for half the year the earth in her orbit is moving in one direction, and for the other half returning in the opposite direction: therefore, for half the year the star will be a little displaced to one side, and for half the year a little displaced to the other side. In fact, it will itself appear to move in a tiny orbit. Knowing this apparent movement to depend really on the earth's movement (since its period is the same for all the stars), we infer that the true place of the star is in the centre of this apparent orbit, and accordingly fixing this spot by its latitude and longitude, we can at any time point the centre of our telescope towards it, and measure the amount of the star's displacement.

This method of investigation confirmed Römer's estimate of the velocity of light, but both need the same correction as to the size of the earth's orbit.

An instructive illustration of aberration is seen in the raindrops falling on the windows of a railway carriage. If the air be still they fall perpendicularly when the train is at rest, but begin to slant as the train moves, till they become nearly horizontal when a high speed is reached, being left behind in the course of their

passage down the glass by the speed with which the window moves forward.

80. The next investigation into the velocity of light was made by M. Fizeau with an experiment of this kind.

Suppose a screen with a small hole in it, through which a strong beam of light is sent on to a reflector placed at a considerable distance the other side of the screen. In M. Fizeau's experiment it was rather more than five miles off. By adjusting the reflector it can be made to send the beam back, not through the same hole but through another of the same size and shape in another part of the screen.

In front of such a screen was placed a wheel toothed like a clock wheel, having each tooth equal in size to the space between it and the next, and so arranged that when the first hole was covered by one tooth the other was just covered by another tooth of the wheel, and that as the wheel turned both holes became visible at the same moment between the teeth. The wheel was so connected with other machinery that it could be caused to revolve as fast or slowly as the experimenter pleased, and also that the number of its revolutions in a given time could be ascertained.

Now, if such a wheel begins to turn slowly, the light returning through the second hole will alternately appear and disappear as each tooth of the wheel passes over the opening and then leaves it clear again. But let the speed be gradually increased until ten of the teeth pass over the hole in a second, and then the light will be seen continuously, because every impression made by light on the retina of the eye remains there for the tenth of a second before it is blotted out,

and if the successive lights follow each other within a tenth of a second it will never be quite blotted out. If the wheel goes on moving just at this pace the light will flicker, but with a little faster movement we soon obtain a steady continuous light.

But now increase the speed very much: let it get faster, and faster, and faster, until, as we watch the steady light coming through the hole, we suddenly find that it is gone, that there is darkness there instead. What has happened now? The light is burning as brightly as ever, the reflector is still doing its work properly. But the speed of the wheel is now so great that by the time the light which passed through when the first hole was clear, has run its ten miles journey, and got back to the second hole, the next tooth has arrived there also, and the passage is barred. Now, knowing the size of the wheel, the number of its teeth, and the number of revolutions it was making in a second when the light disappeared, we can reckon in what fraction of a second each tooth passed through a space equal to half its own breadth, and this will be equal to the time taken by the light to run ten miles. For instance, if the wheel has 400 teeth, and is found to be making $23\frac{1}{4}$ revolutions in a second when the light is thus interrupted, we may reckon thus: the tooth passed through a space equal to half its own breadth in $\frac{1}{800}$ of a revolution, and each revolution took place in $\frac{1}{23\frac{1}{4}}$ of a second. Multiplying these two fractions together, we obtain $\frac{1}{18,600}$ for the fraction of a second in which the light travelled ten miles, and $\frac{1}{186,000}$ of a second for the rate of a single mile's journey.

But let us still increase the speed, and we may reach a point at which the light will reappear. The tooth has now passed through a space equal to its own breadth in the time that the light has gone ten miles, and therefore the next hole is open by the time the light returns. In like manner we should find the light alternately appear and disappear as the hole is covered or passed by the second, third, and fourth tooth in their turn.

81. The velocity of light was estimated by M. Fizeau at 196,000 miles a second, but his experiment was afterwards improved upon by M. Foucault, who, by a very ingenious arrangement of revolving mirrors, measured the velocity of light in a much shorter distance. His experiments, which were considered very conclusive, gave a velocity for light of 185,172 miles a second. This agrees very fairly with the astronomical measurements when they are corrected for the size of the earth's orbit.

These measurements are all made for the velocity of light in air, but by means of M. Foucault's experiment the velocity has since been measured in various liquid and solid substances, in some of which it is found to move more slowly, as if it found some difficulty in getting through.

Having thus formed some estimate of the velocity of the outrunning waves of light, we come to our second problem, the size of the wave lengths.

CHAPTER X.

MEASURINGS—*continued.*

82. The waves of the different coloured rays in the prismatic spectrum are not of the same length. The red or least refracted rays have the longest waves, and the violet or most refracted the shortest. The exceedingly delicate measurement of their actual length was effected by the following means.

83. If a convex lens of very long focal length, such for instance as would be a slice off the surface of a glass globe 100 feet in diameter, be laid upon a flat piece of glass, both glasses being quite smooth and clean, then upon pressing them slightly together a number of coloured rings become visible through the glass, separated from each other by dark rings. The spot in the middle where the two glasses touch, is black, and the rings are arranged round it in the following order, reckoning from the centre.

"1st series, very pale blue, brilliant white, very pale yellow, orange, red; 2nd series, dark purple, blue, imperfect yellow green, bright yellow, crimson; 3rd, purple, blue, grass green, fine yellow, pink, crimson; 4th, bluish green, pale pink inclining to yellow, red; 5th, pale bluish green, white, pink. After these the colours grow paler and paler, alternately bluish green and pink, and can hardly be traced beyond the seventh order."[1]

84. The cause of these colours is successive reflexion from two surfaces very close together.

[1] Herschel.

When the light passing through the upper lens reaches the thin film of air enclosed between the two glasses, part of it is reflected from this upper surface of air, and part passes on to the lower surface, from which a fresh reflexion takes place.

Now, what is it that is thus reflected? A succession of waves.

Let us go back for an instant to the successive waves running outward in otherwise still water, which are represented in Fig. 28. If the first of these waves meets with an obstacle, such as might be presented by a floating buoy or by the bank, a wave of reflexion will instantly begin to run back again away from the obstacle. The original and reflected waves will, according to the law of all reflexion, make equal angles with the opposing surface. As the successive waves touch the buoy, successive reflected waves start on their journey away again.

Returning now to our coloured rings between the glasses; we know that when the light touches the first surface of the film of air, part of it is reflected, that is to say, waves of light of the same velocity and wave length, begin to run back from it; when it reaches the second surface, a second set of waves, again of the same velocity and wave length, start in pursuit of the first, overtaking them at the first surface, and going on with them.

85. If the crests of the second set of waves coincide with the crests of the first, and the troughs with the troughs, the effect will be to produce waves of double height—of double amplitude; but if, on the contrary, the second set are just so far behind the

first that the crests of one set coincide with the troughs of the other, the particles of æther, being pulled both up and down at the same moment with equal force, will not move either way; there will be no vibration, the wave is destroyed, and stillness takes its place.[1]

The question whether the wave crests will coincide or interfere with each other depends on the proportion of the thickness of the film (the distance the light has to run forward and back again) to the wave length. It follows, therefore, that since the colours which make

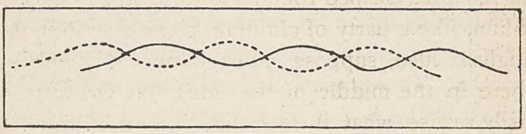


Fig. 30—Interference of two waves differing in phase by half a wave length.

up white light all have different wave lengths, that colour which has just the right wave length to suit the thickness at any point, will gain double its former amplitude of vibration at that point, while other colours whose wave lengths do not suit will have their vibrations, partially or wholly, destroyed by interference. The brightness of light increases with the amplitude of vibration of the particles, so that this double amplitude gives double the brilliancy to this particular colour, and the thickness of the film being the same at the same distance from the point where the glasses touch each other, a ring of this colour will appear at this distance all round the central spot. None of the coloured rings

[1] This is strictly true only when the interfering waves are of equal amplitude, but in the thin films of which we are speaking the difference of amplitude is so small that the conditions are fairly fulfilled.

so formed are of pure prismatic colours, as the other wave lengths that have their amplitude only partially destroyed by interference will still show enough to modify the colour.

Before coming to the actual measurement of the wave lengths, another circumstance must be taken into account, which can, perhaps, best be indicated by analogy.

86. Suppose that a line of people have to push in single file through thick brushwood, and that each man has his arms clasped round the waist of the one in front of him, like a party of children playing at French and English; also, suppose yourself one of them, somewhere in the middle of the line, that you may more easily realise what it feels like. Now, if the hindermost gives a push forward he will push the second against the third, the third will push against the fourth, and so the push, the wave of motion, will pass all along the line, and you, standing in the middle, will feel yourself pushed forward a little from behind, and this we will suppose to be the nature of the forward movement. But as they go forward the first man suddenly comes out into a clearing. We will imagine, to make the illustration more vivid, that he has shut his eyes for fear of the brambles, and is pushing on without any idea that there is a clearing close in front of him. Then the moment the resistance in front of him disappears, he will fall forward a little, and, in falling, will give a pull to the man behind him, and this pull will pass along the line just as the push did before. You in the middle will suddenly be aware that instead of the push from behind, the strongest force acting upon you is a

pull from the front, and you will probably guess, in consequence, that the head of the line has got out of the wood. The pulling wave will be a wave of motion *reflected* back from the surface where the dense medium of the wood touches the thinner medium of the clearing. The pushing wave that ran forward to the clearing is changed into a pulling wave reflected back.

Now if, on the contrary, instead of coming into a clearing, the man at the head of the line had run against something much denser than the brushwood he was passing through, if he had run his head against a tree, a wave of movements would indeed be reflected back through the line, but it would not be a pulling wave. The resistance of the tree trunk, supposing him to come against it with any force, would make him start back; he would push back against the man behind him, and the reflected wave would in this case be one of pushes like the original wave.

The point to observe is that when a wave of motion meets a *denser* medium, a wave just like it is reflected, but that when it meets a *rarer* medium, some change takes place in the reflected wave.

Let us take another illustration. Suppose two men are thrashing together in a barn with the old-fashioned flails, and that their strokes fall alternately in regular time. If one of them hits suddenly upon a thoroughly rotten and crumbling plank in the barn floor, so that his blow does not meet with the resistance he expected, he will be thrown out of time with his companion.

Or if a wood-cutter, hewing at a tree, is giving a succession of regular rhythmical strokes with his axe,

this regular succession will not be interrupted by his meeting with a harder knot in the wood, although each stroke will then have less effect; but if he breaks through unexpectedly into a soft or rotten place, his blow, not meeting the expected resistance, will for an instant be thrown out of time.

Again, suppose a regiment of soldiers in line crossing a sandy beach which is left pleasantly firm by the retreating tide; the column which crosses a quicksand will be thrown out of step with the rest.

Herschel illustrates this point by imagining a series of equal sized balls connected by an elastic string attached to their centres. If a similar separate ball be driven against one end of the line, a wave of "compression" or of "pushing" will pass along the line, and were the last ball of the series free it would start off; but being pulled back by the elastic string, the pull back is communicated again to the other balls, and a "wave of extension" or of "pulling" is reflected back through the series.

If beyond the first series is placed a second series of smaller balls (Fig. 31), leaving space enough for the play of a small ball placed in contact with the first set, then a portion of the original movement will run on, still as a *pushing* wave, through the smaller balls, while a weaker pulling wave is reflected back through the larger. The smaller balls represent a rarer medium, and the pulling wave, the wave reflected from the surface of a rarer medium.

If, however, we change the smaller set for balls still larger than the first, these will represent a denser medium, and while a wave of compression will be sent

forward as before, the last ball of the first set will be driven back by its contact with a larger ball, and the reflected wave will in this case be also a wave of compression.

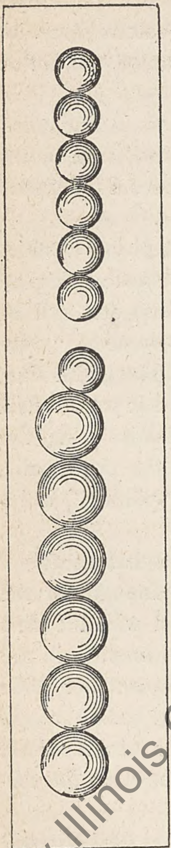


Fig. 31.

Now it is found that waves of light, in the act of their reflexion from the surface of a rarer medium, are in like manner thrown out of time or out of step. A "change of phase," as it is called, takes place, (answering to the change from pushing to pulling in our first illustration), which does not occur in reflexion from the surface of a denser medium. A little consideration will show that this change of phase amounts to a change of half a wave length, for a wave length is the distance from crest to crest, or from hollow to hollow of the wave.

87. Keeping this fact in mind, then, that light undergoes a change of half a wave length in the act of reflexion from a rarer medium—we are at last ready to measure our wave lengths. If the thickness of the air film at any one point is just equal to half a wave length or any number of half wave lengths of red light, then double that thickness, that is the distance run by the light in passing through *and back*

again, will be an equal number of whole wave lengths, and did no change take place at the surface of a rarer medium, then the reflected light from the first surface, and that from the second surface, just a whole wave behind it, would move together in unison, and a red light wave of double amplitude and brilliancy would be the result.

But the wave reflected from the first surface, as the light passes into the film of air, was, in fact, thrown out of step in the act of reflexion, and this change of step is exactly equal to the loss or gain of half a wave length; so that instead of a difference of one wave length there will be a difference of half, or one and a half between the two waves. The crests of the one will coincide with the troughs of the other; they will destroy each other; and instead of a doubly brilliant red light there will be an absence of all red light at this point.

But if, on the other hand, the film be a quarter of a wave length wide, then the double distance will be half a wave, and this, with the addition of the half wave length gained at the first surface, will bring out the waves in unison, and the red light will flash out in double brilliancy. For this result one, or any uneven number of quarter wave lengths, is necessary, as even numbers of quarters are halves.

The diameter of the red rings can be accurately measured, and the curvature of the lens being known, it becomes possible to calculate the thickness of the film under any ring;[1] and as the thickness rises

[1] We will try to gain an idea of the manner in which this calculation is made. Let B D F (Fig. 32) represent a circle of 5 feet radius,

gradually from nothing (at the point of contact of the glasses) we infer that the first or smallest red ring will become visible at the thickness of a single quarter wave length.

In the central spot a double reflexion still takes place, from the under surface of the upper glass and the upper surface of the lower one, but here the distance traversed by the light is so much less than a quarter wave length of any of the colours in light, that

standing on a straight line G H; it is required to measure the distance of the point B from G H. Draw a line A D, the radius of the circle at right angles to G H, join A and B, draw B C at right angles to A D, and B E at right angles to G H. We can measure the length of the line B C which we will suppose to be 3 feet. Then B E C D is

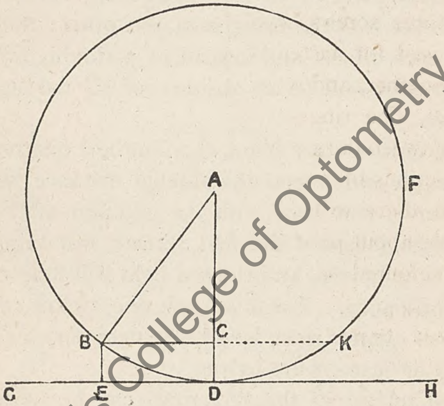


Fig. 32.

a parallelogram, and B E = C D. As radii of the same circle A D = A B = 5 ft., and B E = A B — A C. We have now, therefore, only to find the length of A C. As A B C is a right-angled triangle, we know by Eucl. I. 47, that the square of A B = the sum of the squares of A C and B C. The square of A B is 25 ft., the square of

it returns to the first surface practically in the same phase as when it left it, and therefore is always thrown out of step by the loss of the half wave length at the first surface. In this case all the waves of light are destroyed, and the central spot appears black.

88. These rings may be seen by means of a very simple apparatus. Over a piece of stout card or millboard gum some black paper, upon this lay two clean and bright spectacle lenses, one upon the other, and over these again another piece of millboard with a round hole in the centre, somewhat smaller than the lenses, so as to keep these in place while permitting them to be seen. Then pass through both boards three screws, such as are used for fastening papers together, and screw up tight. The rings will appear between the glasses, and alterations of pressure here and there will make them slide about prettily.

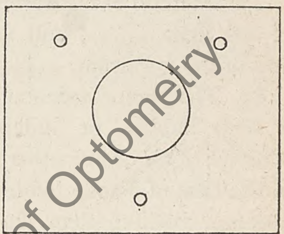


Fig. 33.

If a coloured glass is

B C 9 ft., which leaves 16 for the square of A C, and 4 ft. for the length of A C. Or more shortly, A B = 5 ft., B C = 3 ft.

$$(AC)^2 = (AB)^2 - (BC)^2$$

$$\therefore AC = \sqrt{(AB)^2 - (BC)^2} = \sqrt{25 - 9} = 4.$$

Therefore B E = 5 - 4 ft. = 1 ft.

In using the same method of calculation to measure the thickness of the film of air between two glasses, the curve B D K will represent the curvature of the lens (of which the radius A D is known), G H the surface of the flat glass, and B C half the diameter of one of the coloured rings. Then B E will be the thickness of the film beneath the ring under measurement.

used; the rings will be black and coloured, larger or smaller according to the colour used.

It is possible to get rid of the change of step. If two glasses be used of different density, with a film of intermediate density between them, as, for instance, a film of oil of sassafras between light crown and heavy flint glass, then the two reflexions will be both from denser or both from rarer media. There will either be no change of step, or two changes neutralizing each other. All the light will be reflected instead of being all destroyed, and the central spot will be, not black, but white. The diameter of all the rings will also be changed, as now the half and not the quarter wave lengths will be the favourable thickness.

This method of measurement gives for a wave length of red light $\frac{1}{33866}$, and for violet light, at the other end of the spectrum, $\frac{1}{70555}$ of an inch.

89. The same rainbow colours may be seen in a soap bubble, or indeed in any very thin film, whether of air or any other transparent substance; but in the case of a soap bubble, or wherever the film is of a denser medium than the surrounding substance, the change of step occurs not at the first but at the second surface. In all other respects the phenomena are exactly similar.

90. The colours seen on mother-of-pearl or other very finely grooved surfaces are caused in somewhat the same manner, by the interference of waves successively reflected from the edges of the grooves, which must be near enough together to return waves with very little difference of amplitude.

91. We have now the velocity estimated at about

186,000 miles a second, and the wave length for red light at $\frac{1}{33866}$ of an inch. In 186,000 miles there are 11,784,960,000 inches, and in every inch are 33,866 wave crests. It therefore follows, inconceivably great as are the figures, that when we see red light 399,109,455,360,000 waves must enter our eyes in every second, and this is also the rate of vibration of the luminous particles which emit the light.

Such are the delicate measurements made practicable by mathematics, the marvellous instrument which enables us as well to gauge the star depths, as to declare the thickness of a soap bubble.

Beginners are sometimes perplexed when, on working through these calculations, they find that their results agree only in the larger figures with those sometimes given in books. The explanation is that these sums are generally done by logarithms, which begin at the larger end, and are not worked through down to the hundreds, tens, and units, but stated as round numbers.

CHAPTER XI.

DIFFRACTION.

In the daylight or with any of the ordinary artificial means of lighting that are used, the light is so generally diffused and so frequently reflected among many objects that the action of every point of light is masked by the action of every other, and we clearly may expect to learn more of what this action is by isolating

a single point of light and studying its phenomena alone. These phenomena are very various and some of them very complicated. Two or three only of the simplest can here be described.

92. If we close the shutters of a room into which the sun is shining, and admitting a sunbeam through a small hole let its light fall upon a screen of white paper held at right angles to the beam, it will appear as a small bright circular disk. It is better to fit a lens into the hole of the shutter. Then the focus of the lens will be a small brilliant point, the whole light from which, spreading in a cone, is received upon the screen.

93. If we now cut off some of the light by introducing a solid object into its path, and examine the shadow thrown upon the disk, we find that instead of having a sharp and definite outline the extreme edge of the shadow is misty and undefined, and fringed by rainbow coloured bands running parallel to the shadow in the lighted part of the disk, and growing gradually fainter as they retreat from the shadow.

By placing a red glass in the path of the light we change the white disk into a red one, and the rainbow fringes give place to a series of bright and dark bands.

To understand the cause of these appearances, we must, as usual, go back to consider the nature of the outflowing light.

At the focus of the lens is an image of the sun, formed by the crossing at this point of all the rays of sunlight which came through the hole in the shutter. This image throws out, not a sphere, but a cone of

light, made by the further passage of the rays after crossing. The cone of light consists of a series of waves flowing outwards from the focus towards the screen. For the sake of simplicity we suppose the light to pass through a red glass which sifts the rays, allowing only waves of a certain length to pass.

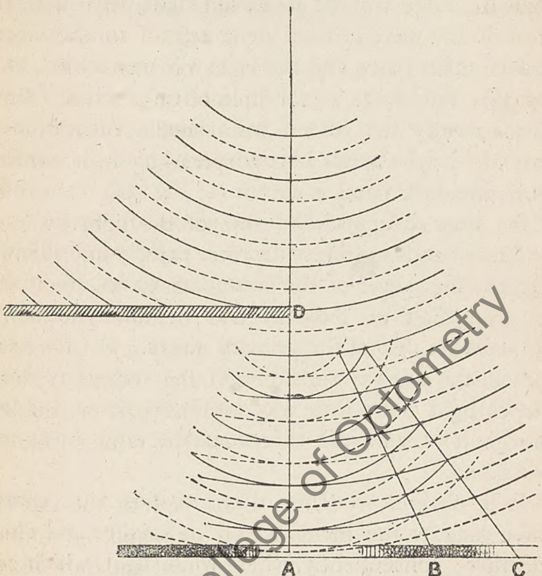


Fig. 34.

Some of these waves, which break partly upon the screen and partly upon the lighted side of the object casting the shadow, are represented in a greatly exaggerated form in Fig. 34.

The dotted lines represent the troughs of the waves, the continuous lines the crests. Where the light

passes the edge of the object, a series of secondary waves is formed, which spreading spherically, intersect the primary waves and reach the screen along with them. Where the crests of the primary and secondary waves cross each other, the light will be intensified, or again, where the troughs of the two sets of waves coincide, there will be increased light, but where the crest of one wave crosses the trough of another, interference takes place and the light will be dimmed, or, if the two lights are equal in intensity, extinguished. Consequently the screen will show a succession of dark and bright bands beyond the edge of the shadow. Only one dark band is shown (B, Fig. 34) on account of the large scale on which the waves are drawn.

These bands or fringes decrease rapidly in brilliancy, because the power of the secondary waves diminishes in proportion as the direction of their motion is farther from that of the primary waves. For the same reason, the sideway spreading cf the secondary waves carries light but a little way within the actual shadow, though it is sufficient to render the edge misty and undefined.

It is obvious from the diagram, that with shorter wave lengths the bands would be smaller and closer together: consequently, where white light, which contains all the wave lengths, is employed, places that are dark to red light may be light to blue, and, in fact, we find by experiment that instead of simple bright and dark bands we have a series of rainbow-coloured fringes round the shadow.

The edges of the bright and dark bands are not sharply defined, but fade gradually into each other.

We should expect to find this so, for since the centre of the bright band is the point of greatest harmony, and the centre of the dark band the point of greatest interference between two sets of waves, it is obvious that between these points there must be partial interference gradually increasing or diminishing in amount as we pass from one band to another.

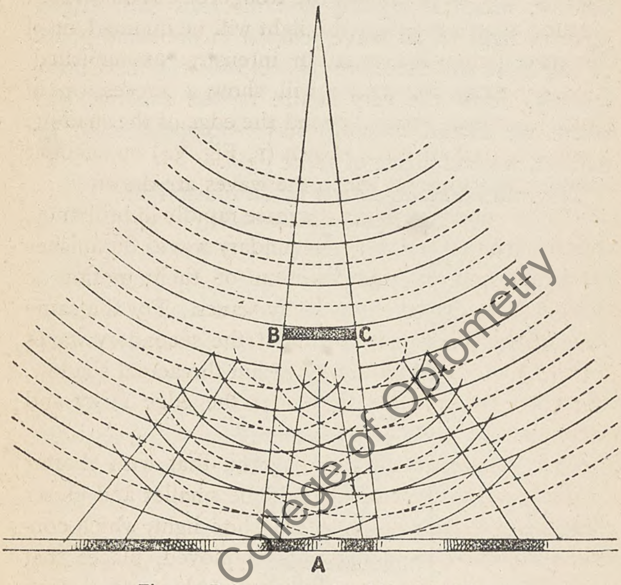


Fig. 35—B C represents the width of the hair.

94. When the shadow is cast by a very narrow object, such as a hair, the exterior fringes caused by the interference of the primary and secondary waves are seen on both edges of the shadow; but in this case we find further that the two series of secondary

waves, starting from each side of the hair, intersect and interfere with each other within the limits of the shadow itself, making a series of interior fringes (Fig. 35).

There is, moreover, this peculiarity. As the secondary waves start from each side at the same instant, in the same phase of vibration, and travel with the same velocity, the central spot A of the shadow, which is equally distant from both edges, receives light of all wave lengths in the same phase of vibration, and therefore reflects white light. Consequently, down the very centre of the shadow, just where we should naturally have supposed it to be darkest, we find a line of white light.

This will be made clearer by an illustration.

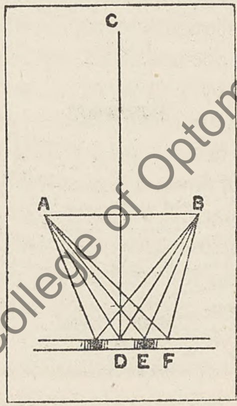


Fig. 36.

Let A B, Fig. 36, represent an obstacle on a road, and suppose that two men walking together from C pass one round each end of it and meet again on the other side at D. If they leave A and B precisely at

the same moment with the same foot forward, and take steps of exactly the same length, they will both reach D with the same foot forward, because they will both have come just the same distance. But if they meet at E instead of at D, the man from A will have to take, let us say, one step more than the man from B, because he has a longer distance to come: at E, therefore, we shall find that one man has his right foot forwards and the other his left: they are out of step.

If, however, they meet at F, the man from A will have to take two more steps than the man from B; he will have his right foot forward again, and they will be in step.

Now, waves of light are out of step and interfere with each other when their phases differ by half a wave length, and consequently we find that the interior dark bands (Fig. 35) occur where their distance from B and from C differs by half a wave length. The figure shows that the actual width of the bands must depend on the distance of B C from the screen.

These interior fringes can only be produced where the shadow is narrow enough to allow the secondary waves to meet before their rapidly diminishing strength is too far spent to render their interference visible.

95. In the first of these cases—that of the exterior fringes—we have the interference of primary with secondary waves. In the second—that of interior fringes—the interference is between two series of secondary waves. The first was caused by one edge of a shadow, the second by the two edges of the same shadow brought very near together. We have yet a third case to investigate. What will be the result of

gradually bringing together the edges of two different shadows?

Draw on two cards two sets of bands like those in Fig. 37, roughly shaded to show their degrees of darkness, and let the darkest band be to the right hand on one, and to the left hand on the other.

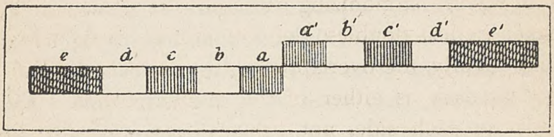


Fig. 37.

These are to represent the exterior fringes of two shadows, not yet near enough together for interference. Lay them as in the figure, so that the lightest shadow bands lie side by side in the middle without overlapping.

Now, narrow the slit of light between the two edges by slipping the cards further across each other till the pale shadow bands on each side, *a a'*, lie over each other. Let us see precisely what is the state of things here. Each of these two pale shadow bands is formed by the interference of secondary with primary waves, and when they overlap, the interference of each set of secondary waves is with the *same* primary waves. The secondary waves in this case are in harmony with each other, having travelled an equal distance from their origins, the edges of the slit, but are out of harmony with the primary waves.

If the one set of secondary waves had been as strong as the primary, we should have had complete interference and absolute blackness along the shadow line, and in that case the introduction of the second set of

secondary waves would have partially restored the light, by harmonizing with and strengthening one of the contending parties. But the primary waves, having a much greater amplitude, and therefore intensity, than the secondary, the light was only slightly dimmed by the first interference, and the addition of another set of waves, harmonizing with and strengthening the weaker series, doubles the amount of interference. Consequently, the overlapping gives us a central band twice as dark as either of the original bands. The bands on each side, not having been yet affected, remain precisely as they were.

Now slip the cards on again till each pale shadow band coincides with a light band, a' with b and a with b'. What have we here? The light band means harmony between the primary waves and one set of secondaries. The other set, represented in the pale shadow band, is out of harmony with both.

If the second set were equal in strength to the first, all it could do would be to annihilate these, and leave the primary waves alone; but the second set is not so strong as the first, being farther from its source and farther from the direction of the primary waves. Consequently it only partially interferes with the first secondaries, and the result is a central light band of double width, but not so bright as the other light bands d and d', which are produced by the harmony of the primary waves with the intenser part of the secondary waves, and are not interfered with at all.

Move the cards again in the same direction till the first shadow band on each side, a and a', corresponds with the second on the other, c and c'. The light

bands, *b*, *d* and *d'*, are now all bright, since all the light that reaches them from the primary and all the secondary waves is in harmony, but in the dark bands the light of the primary waves is out of harmony with both series of secondary waves. The visible result here depends upon the relative intensity of the waves. If the intensity of vibration of the primary waves is *equal* to the sum of the intensities of the secondary waves the interference will be complete and the band will be black. If it is *greater* there will be a residue of light from the primary waves, which will diminish the blackness; if it is *less*, there will be a residue of light on the side of the secondary waves which will likewise diminish the blackness.

96. These bands and the series of changes here described may be seen under favourable circumstances without any apparatus at all. On looking through the fingers at any bright light, such as a sunny white wall, delicate shadow lines become visible round the curves of the fingers, separated from them and from each other by bright lines. The eye and hand should both be in shadow, and some attention must be paid to the focussing of the eye most favourable for seeing the lines distinctly. On gradually approaching two fingers to each other, all the changes above described may be seen. First the central dark line, caused by the overlapping of the two pale shadow lines, then the central space of double width and dimmed brightness, and finally two very dark lines between three bright ones. It is difficult to bring the fingers still nearer without closing the slit altogether, but it might be done with a slit that had sharp edges.

If instead of looking at a white surface, we look through the chink between the fingers at a distant candle or gas light, we shall see a most beautiful and brilliant spectrum.[1]

97. We have not done yet with the appearances of light seen through a narrow slit. Simply looking through the fingers in broad daylight, two shadow bands round each finger are probably all that can be distinguished, but if we transfer the experiment to our cone of red light in a dark room, we may obtain a considerable series of dark and bright bands, gradually diminishing in intensity. Now the secondary waves, which, by their intersections with the primary waves, form these bands, spread spherically from their point of origin, and therefore run as far into the shadow as they do out into the light. Consequently, if we gradually narrow the slit, letting the 1st, 2nd, 3rd bands of each side pass one after another into the opposite shadow, the secondary waves which formed these bands will intersect and interfere with the other secondary waves which they find within the shadow, giving rise to a fresh set of interior fringes. If we go on narrowing the slit until *all* the shadow bands have run over into the opposite shadow, we shall be left with a brilliant central line of light, formed by the overlapping of the first bright band on each side, and a series of dark and bright bands on each side of it, continually diminishing in intensity and stretching away into the shadow on either side.

98. When the light passes through several fine slits placed closely side by side, as in a fine grating, a series of bright and dark bands is also formed,

[1] The experiment is best tried in a church, as the distances are great.

though their origin is in this case more complicated, and when the red light is replaced by bright white light, the bands change to a series of brilliant spectra, all having their violet ends turned inward towards the light.

99. We have learned already (36) that spectra produced by refraction through prisms vary in length or amount of dispersion with the material of the prism, and they vary also in the proportion of length of the different colours; but these diffraction spectra, being produced simply by the interference of light waves in the air, are free from such variations, and the position occupied by any colour being due solely to its wave length, they are therefore often preferred for the study of spectrum analysis.

100. It is not always possible for the student to command a dark room at his pleasure; indeed, it is a matter of considerable difficulty to make a room perfectly dark; but the principal phenomena of diffraction may be easily observed by means of a simple pasteboard tube, blackened inside and having its ends closed by moveable caps.

Make such a tube about 12 inches in length, and with a sharp penknife or razor cut a single very fine slit in the cap at each end, and place them parallel to each other; on looking through it at the sun, a series of vivid and beautiful spectra will be seen.

For observing the diffraction caused by a single edge of a shadow or by a hair, it is better to fit a small lens into the cap farthest from the eye, then the object to cast the shadow can be placed in the body of the tube. The experiments can be varied at pleasure, by making

caps with apertures of different shapes or numbers, and by admitting the light through coloured glasses. You will of course not look at the sun through a lens without protecting the eye by deep-coloured glass.

A word of caution will perhaps not be out of place. Do not be disappointed or imagine your experiments a failure if you see little or nothing at the first glance. These phenomena are possibly new to you, and delicate lines are not always instantly detected by an unpractised eye; but watch the edge of the shadow with attention for a few minutes and you will probably be repaid by an increased power of seeing.

101. Reasonings of the same kind as those given above will explain most of the phenomena of diffraction, but if the light is admitted through openings of different forms or through several openings near together, or if the shadows are thrown by slender objects of irregular shapes, such as feathers or lace, their diffraction spectra, interlacing and interfering, may produce figures of the most complicated or most fantastic shapes; and it becomes proportionately difficult to calculate them beforehand, as any number of series of secondary waves from different points may reach the screen together.

102. For instance, when the shadow is thrown by a tiny circular disk, the secondary waves starting from every point round its edge will meet and cross on every point of the shadow as well as on every point for a little distance beyond its margin. In this case coloured rings are formed both behind and around the disk, and if a distant light is looked at through a scattered crowd of tiny round bodies, their

rings blend together to form a large coloured circle round the light. This is the origin of the halos occasionally seen round the sun and moon in a fog, where the diffraction is caused by minute globules of water in the air, or round a candle when the eyes are misty. It is easy to produce an artificial halo by breathing on a flat piece of glass and looking through it at a flame.

If you will procure a little 'lycopodium' from the chemist's, and, scattering it on a piece of window glass, look through it at a distant candle, you will see a beautiful halo of coloured rings. The powder holds on securely enough for a little while. If the powder be shaken across a sunbeam, you will be able to observe for yourself the formation of a halo in the air.

When the attention has once been called to the beautiful phenomena of diffraction, they will be observed everywhere: almost every flash of bright reflected light will betray colours, and all the vivid spectra of the diffraction grating will be readily detected in the passage of direct sunlight through the half closed eyelashes.

CHAPTER XII.

THE SPECTRUM.

103. Hitherto, we have spoken of light as if it were always one and the same thing, but practically we know that there is much difference between lights. We can distinguish the light of a candle

from that of a lamp, an oil lamp from a spirit lamp, both from the light of gas, or magnesium wire, or of the electric spark. The coloured lights used in fireworks are produced by the burning of different chemical substances; and we now desire to know what are the real differences between the obviously distinct kinds of light derived from these and other sources.

The answer to this question is afforded by the spectroscope.

104. It has been already stated (37) that the spectroscope is an instrument furnished with prisms for the purpose of examining the *spectrum* of any kind of light. In the simplest form of spectroscope, the light to be examined is first admitted through a very narrow slit into a short tube, whose other end is fitted with a lens, having a focal length of the length of the tube, so that the slit is just in the focus of the lens. The object of the lens is to render the rays which emerge through it parallel, that the light may not be weakened by divergence.

105. The light which comes through the tube is next caused to fall upon a prism, of which the refracting edge or angle (the edge in which the two refracting surfaces meet) must be set parallel to the slit. If the prism (always keeping the refracting edge parallel with the slit) be turned round upon itself, the spectrum or band of dispersed light formed by it will move round also; but it cannot be brought very near to where the unrefracted light would fall if there were no prism. When the spectrum approaches within a certain distance of this place it begins to

move away from it again even though the prism be still turned in the same direction. The point at which the spectrum begins to reverse its movement is called the point of minimum deviation, and is that at which the rays entering and leaving the prism make equal angles with the two refracting surfaces. In this position the prism must be fixed. A cover

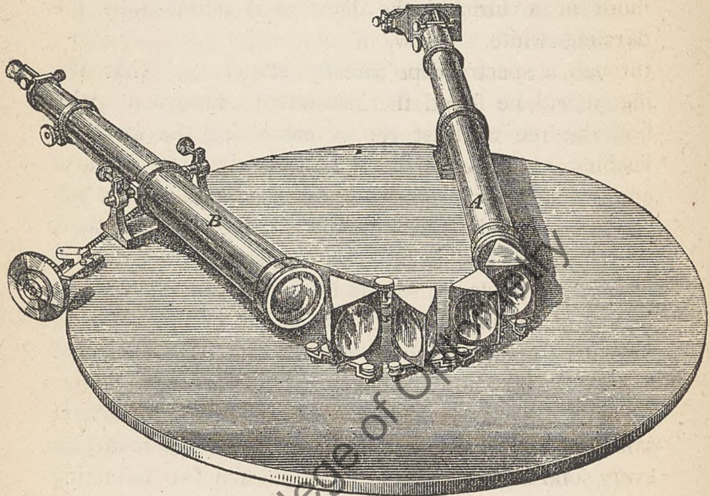


Fig. 38—Kirchhoff's Spectroscope.

blackened inside to exclude stray light is placed over all, having two holes in it, one for the tube to pass through, and an eye-hole just where the spectrum falls, through which to view it.

In more elaborate spectroscopes the dispersion is increased by passing the light through many prisms,

and the spectrum magnified by viewing it through a telescope.

106. It is well known that a solid substance becomes luminous, gives out light, when it is heated. For instance, a lump of coal is visible only by reflected light as long as it is cold, but when it is heated in the fire it begins to give out light. It is red at first; but if heated more and more in a furnace the light at last becomes a dazzling white. Now, if the coal be observed through a spectroscope in all the stages of its heating, it will be found that when it first becomes red hot, the red or least refrangible rays become first visible; as the heat increases, the orange, yellow, and green colours appear also, till at last, when it reaches white heat, all the colours of the spectrum are present in its light.

107. We have in such a spectrum light of every degree of refrangibility between the two extremes of visibility; this is called a continuous spectrum, and a like continuous spectrum is shown by every solid or liquid substance which can be brought to the same degree of heat. At the same temperature every solid and liquid substance emits the same kind of light.

108. But when instead of a solid or liquid substance, we observe *gases* or *vapours* heated till they become luminous, we find quite a different phenomenon. They for the most part give out light not of every refrangibility, but only of certain definite refrangibilities—not of every wave length, but only of certain definite wave lengths.

109. For instance, if common salt (chloride of sodium) be heated till it turns into vapour, and the light of the glowing vapour be examined through a spectroscope, the whole light from it will be found situated in the yellow of the spectrum.

By heating a solid more highly we get more refrangible rays, but no change of temperature will show either red, blue, or violet rays in sodium vapour; it will always give the same band of yellow light, and nothing else. When the spectroscope has a great dispersing and magnifying power, the single yellow band may be seen to be composed of several fine lines of yellow light, and these are always situated on precisely the same points in the spectrum, answering to precisely the same wave lengths.

If the salt is heated in a common candle flame, the continuous spectrum of the candle is visible as well as the bright yellow sodium band, but a gas burner, known as Bunsen's burner, which gives a colourless flame, is most convenient for the purpose of these experiments.

When the vapour of lithium is observed, it is found to give a red and a yellow line: the vapour of each substance has its peculiar set of lines, and in some cases these are very numerous; thus iron vapour gives not less than 450 lines; but in every case all the different lines are so absolutely fixed to their proper places that they can always be known by their position on the spectrum, and may be recognised at a glance by those who are acquainted with them. Many hundred lines peculiar to different substances have been mapped with great accuracy.

110. Mixing different substances together does not confuse their lights: each still gives out only light of those wave-lengths or refrangibilities which are proper to it, and the spectrum of a flame in which many vapours are burning will show the lines of all ranged out in their proper places. Very minute quantities of substances will show themselves by the peculiar refrangibility of their light, and thus the spectroscope becomes the most delicate analyser of compound substances.

111. Besides these *continuous and bright line spectra* there is a third class, known as dark line or *absorption spectra.*

The subject of Absorption of Light has already been spoken of in the chapter on Reflexion. We have seen that all coloured substances exercise a selective power upon the light, and absorbing light of certain colours, that is of certain wave-lengths, reject the rest, which are reflected from it and which constitute what is called the colour of the object.

Now the vapours of the elements exercise a similar selection upon the rays of light transmitted through them: each of them, while transparent to all the rest of the continuous spectrum, absorbs wholly or in great part the light of those special refrangibilities which it gives off when rendered luminous by heat. So, if the spectrum of a flame be looked at through a vessel containing cool sodium vapour, the continuous spectrum of the flame will be found interrupted by a black band situated precisely on that place in the spectrum where the yellow sodium band occurs. The vapour has permitted all the rays from the flame to pass through

it except those ordinarily given off by sodium vapour.

The same will be found true of other vapours : each stops its own light : and if there are mixed vapours in the vessel, the dark lines produced by their absorptions may all be recognized in their own places upon the continuous spectrum.

There are, then, these three kinds of spectra :—*continuous spectra*, produced by incandescent solids or liquids,—*bright line spectra*, produced by luminous vapours,—and *dark line*, or *absorption spectra*, produced by the light from incandescent solids or liquids seen through certain media.

It is found that not only vapours, but some other media called transparent, are transparent only to light of certain wave-lengths ; thus blood and some other liquids give characteristic absorption spectra.

112. It follows from what has been said above, that the nature of anything emitting light may be determined by the spectroscope. If its spectrum be continuous, we recognise it for incandescent solid or liquid; if of bright lines, we may be able to pronounce not only that it consists of glowing vapour, but what the vapour is; and if of dark lines, that light of a continuous spectrum has at some period of its journey to our eyes passed through vaporous or other transparent media, and we may also state of what the media consisted.

113. The first eager inquiry then is, which of these three kinds of spectra is given by the sun's light? The spectroscope immediately answers, an absorption spectrum. The solar spectrum is crossed

by hundreds, nay, thousands, of fine dark lines, and many of these lines have been identified, so that we can say, the sun's light on its way to us has passed through vapours of iron, sodium, nickel, manganese, hydrogen, &c. Are these vapours, then, in the sun's atmosphere, or in that of the earth? If they belong to the earth's atmosphere, the spectra of the stars' light which comes also through our atmosphere will show the same.

114. We ask the stars the question by means of the spectroscope. They also show absorption spectra, but not the same as the sun's, and the stars differ one from another. We presume, then, that the greater part of the lines are due to vapours in the atmosphere of the sun and stars: some belong to that of the earth, and these are more conspicuous and numerous when the sun is near the horizon, as its light then passes through a greater thickness of the atmosphere than when it is high in the sky.

The moon and the planets, shining by reflected sunlight, only give us fresh editions of the solar spectrum.

115. But how wonderful are the revelations thus made to us of the constitution of the sun and stars. They glow with a heat intense enough to keep substances, such as iron, constantly in the condition of vapour in their atmospheres, these vapours acting as absorbents upon the light emitted by the glowing nucleus, and thus producing the dark lines. The absorbing vapours are themselves luminous, and give out light of precisely that refrangibility which they stop; but while the light of the nucleus illuminates all the rest of the solar spectrum, only this comparatively

faint light from the cooler outskirts of the sun's atmosphere falls upon the dark line spaces, which, therefore, appear dark by comparison. And from the position of the dark lines we know to a considerable extent *what the sun and stars are made of*, and that they are made of much the same materials as our dwelling place, the earth.

We see, then, that the visible universe is not only governed throughout, as we are taught by astronomy, by the same laws of motion, but that it is apparently constructed throughout of the same materials.

In addition to its investigations into the mysteries of light, the spectroscope affords valuable information on the other properties of the solar rays—heat and chemical action—with which we are not now immediately concerned.

If, as is not unlikely, the study of the spectrum excites special interest and delight, the reader is recommended to turn for further information to the treatises of Professor Roscoe or Dr. Schellen.

CHAPTER XIII.

THE RAINBOW.

The extreme beauty of the rainbow, and the circumstances under which it appears, have always rendered it one of the most attractive and most constantly observed of all optical phenomena; and though the account of its formation is a little complicated, we are now in a position to understand something about it.

116. It is well known that the rainbow is only seen when the sun is shining on drops of water, as in a rain cloud, the spray of a fountain or waterfall, or other cases where water is finely divided, and that the spectator sees a bright rainbow *only when his back is turned to the sun.*

117. It is produced by the refraction and reflexion of rays of sunshine within the drops; and we must begin by tracing the paths of the incident rays in a drop of water. For the sake of simplicity, we will first consider the case of red rays only, as if the light had passed through a flat piece of red glass.

When a number of parallel red rays fall upon the drop, they are each divided at the first surface, part being reflected and part refracted. The entering rays pass through to the further side of the drop, and are there again divided, part being reflected in the interior and part passing out. Those which are reflected return to the front of the drop (at an angle equal to that of their incidence on the reflecting surface) and are divided for the third time, part suffering a second reflexion, and part being refracted. (See fig. 39.)

118. Now, it was said in the last chapter (105) that there is one position of a prism in which the *deviation* of light, or the angle between the path of the refracted ray and that which it would have pursued if unrefracted, is less than in any other. It is that at which the incident and refracted rays make equal angles with the refracting surfaces. This is called the position of *minimum deviation.*

119. Rays which are refracted in this position deviate less than those in any other, and rays which

fall very near to this point have very little difference of deviation ; consequently, there is—just about the place of minimum deviation—a bundle or pencil of rays, having their deviations almost equal to one another, and therefore being very nearly parallel. And since parallel rays carry much brighter light in their journey through space than those that are weakened by divergence, and the more nearly rays approach to parallelism the brighter will be their effect, these almost parallel rays are called *effective rays*.

Exactly the same thing happens with a sphere as with a prism ; the pencil of rays issuing at the point

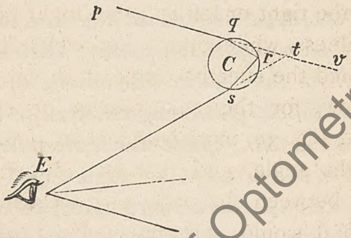


Fig. 39.

where the angles of incidence and emergence are equal, consists of *effective rays*, having almost exactly the same deviation, and therefore being very nearly parallel.

p q r s E, Fig. 39, is intended to represent the course of the effective red rays in a drop of water.

The sun's rays, coming from beyond *p*, shine upon all that side of the drop, and are everywhere being refracted and reflected, but to an eye stationed at E, only those red rays are *effective* which, entering about *q*, where they undergo refraction, are reflected from *r*,

and issue from the drop at *s*, for these only fulfil the condition of entering and issuing from the drop at equal angles.

It follows, then, that an eye so placed as to receive the *effective* rays issuing from the drop of water, will see much more brilliant red light than an eye which receives any of the other rays.

When the morning sun is shining upon dewy grass you may observe that some of the dewdrops reflect dazzling light of one colour or another, while others, though visible, have no special brilliancy. In this case your eye is so placed as to receive effective rays from the bright drops, but not from the others. Move a little to the right or left and the bright drops lose all their vividness, while others, for which the eye has now assumed the effective angle, flash out instead.

120. Now, for the red rays to be effective the angle $p\ t$ E, Fig. 39, must be equal to $42° 2'$, or nearly half a right angle, and therefore the *deviation* (or difference between the path of the refracted ray and that which it would have pursued if unrefracted) represented by the angle E $t\ v$, is equal to $137° 58'$.

The size of these angles varies with the refrangibility of the coloured rays. For violet rays to be effective the angle $p\ t$ E must be equal to $40° 17'$, and the angle of deviation, E $t\ v$, to $139° 43'$. The angles for the other colours of the spectrum are intermediate between those for the red and the violet.

In Fig. 40, the line E A is drawn parallel to the line P V, and therefore[1] the angle A E V is equal to the angle P V E, which is $42° 2'$ for red light. If the

[1] By Eucl. I, 29.

line E V could move round upon the point E, like the leg of a pair of compasses, keeping always the same angle, 42° 2′, with E A, it would describe a circle; and a drop of water on any point in this circle would return effective red rays to an eye situated at E.

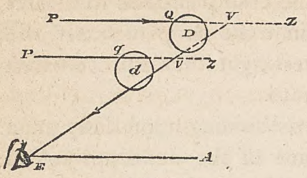


Fig. 40.

At some time in the morning or evening, when the sun is shining, stand in the open air with your back to the sun, look at the shadow of your own head, and observe what would be the position of a line joining your head and its shadow. This will correspond to the line E A, Fig. 40, since the sun is directly behind E.

Place your walking stick or umbrella at an angle of 42° 2′ with this line, with its handle resting on the bridge of your nose between your eyes, and, keeping always the same angle, move its further end round in a circle. It will point to the precise place where the red arch of a rainbow would be visible were there any rain falling; but the rainbow is usually only seen in that part of the circle which is above the horizon, not in that which lies on the ground.

In like manner, if the stick is placed at an angle of 40° 17′ with the line joining your head and its shadow, —that is, at the effective angle for violet light,—it will point in its revolution to the position in which the violet arch of a rainbow would be seen, and since the angle 40° 17′ is smaller than the angle 42° 2′, it follows that the violet arch would be inside the red arch.

121. If rain were falling, every drop of water pointed to by your stick during this experiment, from those close to your eyes to the farthest you can see, would help to produce the circles of coloured light, for it is not the drops in a single plane only that fulfil the conditions necessary to transmit effective rays. In Fig. 40 we see that any number of drops threaded upon the line E V will all hold the same angular position with regard to the sun and the eye, and that the arguments given above are equally true

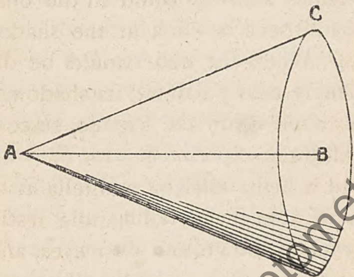


Fig. 41.

for each of them. The surface which produces the red arch is therefore not a plane, but the surface of a cone, Fig. 41, of which the axis A B corresponds to the line E A, Fig. 40, the angle C A B to the angle V E A (42° 2′), and therefore the whole angular opening to twice this angle, viz., 84° 4′.

The surface of a smaller interior cone, having the same axis, but with its angular opening 80° 34′, viz., twice the angle for effective violet rays, will be the surface producing the violet arch. Between these two, but all upon the same axis, are the cones producing

the intermediate coloured arches, and the apex or point of all the cones is in the eye situated at A, Fig. 41.

122. We have seen that this axis E A, Fig. 40, is always parallel to the sun's incident rays, represented by the line P V. Thus, when the sun is on the horizon, and its rays level, the axis is level also, and a rainbow might be seen as a full semi-circle; but as the sun rises in the sky and its rays pour downwards upon the earth, the further end of the axis with all its cones sinks downward also, and any rainbow that may be seen has less of the arch visible above the horizon. When the sun reaches an elevation of 42° 2′, which is nearly half-way up, the whole series of cones has sunk below the horizon, and no rainbow is visible. Try the experiment with the walking stick when the sun is high, and you will find that, owing to the shadow of your head falling near your feet, the stick will point to the ground during the whole of its revolution. This explains why the rainbow is seen in summer only in the morning and evening.

123. From all that has been said above it may be perceived that no two people ever see the same rainbow: each person has his own rainbow, his private set of cones which meet in his eye only; and any of the same drops which are sending effective red light to him may be sending effective light of any other colour to others who stand near him. But every one not colour blind will see a rainbow at the same time, since the same conditions are present for all.

124. Hitherto we have disregarded all but the effective rays, but the rays transmitted at other angles

through the drop do bring us light also though it is much less bright.

Since the effective rays are at the position of *minimum deviation*, it follows that all the other rays, whether incident on the drop above or below these, must have a larger deviation, E V Z (Fig. 40), with the path that would be followed by unrefracted rays. Consequently, they all issue from the drop towards the eye above the effective rays. In the case, then, of the drops producing the red arch these ineffective rays will all pass above the eye of the observer, and will not be seen. This gives the red arch a sharply defined outer limit, beyond which the sky is somewhat darker than elsewhere, thus making the rainbow look brighter by contrast. But in the case of drops situated on the interior cones their dim red rays reach the eye along with their own effective coloured rays, and the colour of each arch is dimly spread over those within its circumference: this causes a gradual shading off inwards of the rainbow colours, none of which is pure, but the outermost red.

So far, then, we have found the rainbow to be due to the refraction of solar rays which have undergone a single reflexion within drops of water, and we have found that its appearance and colours depend upon two causes: the different refrangibility of the colours of the spectrum and the position of minimum deviation.

125. We have accounted as yet for but a small proportion of the incident light, and must next consider what are the effects produced by light which suffers *two* reflexions within the rain drops. Fig. 42 represents

the path of rays which, after undergoing two internal reflexions, finally issue from the reflecting surface at an angle equal to that at which they entered, and, therefore, fulfil the conditions required for effective rays.

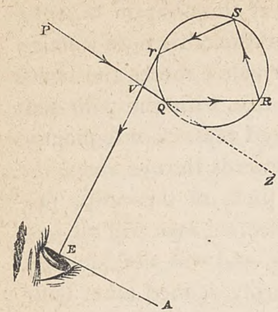


Fig. 42.

In this case the angle between the axis E A of the cone and the centre of the effective red rays is 50° 58′, and the angle for effective violet rays 54° 9′; therefore in this case the red cone is the smaller of the two, but both are larger than those we have already considered. This doubly reflected light produces therefore, when the illumination is strong, a larger secondary and fainter rainbow in which all the colours of the primary rainbow are reversed, the violet arch being outermost.

126. The *deviation* in this case is the angle 360° – Q V E (Fig. 42). (Were it bent completely round the circle of 360°, it would continue in its original unrefracted path P Z, but it comes short of this by the angle Q V E.) From this we can see that the *ineffective* rays, all of which suffer a greater deviation, will more nearly approach the direction P Z, and since they all issue below the effective rays, only those from the drops on the outer cones can reach the observer's eye as dim light: this gives a defined limit to the *inner* edge of the secondary rainbow, with comparative darkness beyond it, while the light of the outer edge of each colour will fade gradually upwards.

The angles given above precisely define the width of the bows and their distance apart. The width of the inner or primary bow is $42^\circ\ 2' - 40^\circ\ 17' = 1^\circ\ 45'$; the width of the outer or secondary bow is $54^\circ\ 9' - 50^\circ\ 58' = 3^\circ\ 11'$; and the space between the bows is $50^\circ\ 58' - 42^\circ\ 2' = 8^\circ\ 56'$. This space is, as said above, darker than other parts of the sky. A magnified drop from each of these bows is seen in Fig. 43.

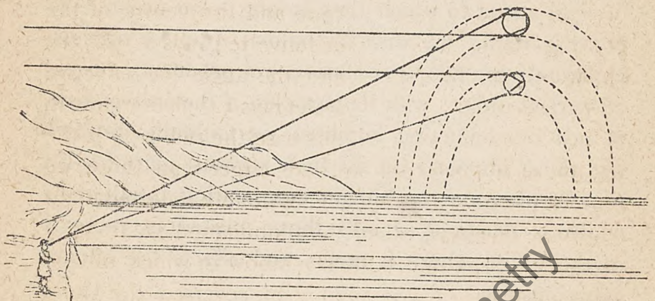


Fig. 43.

127. Now we may fairly argue that, supposing the illumination to be strong enough to bear so much division, we ought to see more rainbows, produced by three, four, five, or more internal reflexions. On calculating the positions in which to look for these, it is found that the third and fourth will occur between the observer and the sun, so that their faint light must be lost in the stronger sunlight. The fifth, which is on the same side with the first and second, has been sometimes seen in waterfalls; and it is said that by throwing the sun's rays on to a jet of water in a dark room supplementary rainbows have been counted up to the seventeenth.

Besides the rainbows produced by refraction, some bows are occasionally seen within the primary which appear to be caused by diffraction. It is this cause, as we have seen, that gives rise to halos, and other remarkable phenomena, such as parhelia, appear to be due to it also.

128. Here let us pause from the consideration of details, and think for a moment of the vast ocean of light waves to which they belong;—an ocean ever heaving round us, with its billows, ripples, ripplets, apparently in endless confusion, yet producing results of perfect order; with its particles, if themselves held at rest by conflicting impulses, yet faithfully forwarding those impulses on all their various journeys, till they break upon the human eye, bearing intelligence which is telegraphed into those mysterious recesses of the brain, where it meets and affects the human consciousness.

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